A Marine Biogeographic Assessment of the Northwestern Hawaiian Islands

Alan Friedlander
NOAA Center for Coastal Monitoring and Assessment
Biogeography Branch

Kaylene Keller
NOAA Office of National Marine Sanctuaries
Papahanaumokuakea Marine National Monument

Lisa Wedding
NOAA Center for Coastal Monitoring and Assessment
Biogeography Branch

University of Hawaii at Manoa

Alicia Clarke
NOAA Center for Coastal Monitoring and Assessment
Biogeography Branch

Mark Monaco
NOAA Center for Coastal Monitoring and Assessment
Biogeography Branch

NOAA TECHNICAL MEMORANDUM NOS NCCOS 84

Citations

Citation for entire document:

Friedlander, A., K. Keller, L. Wedding, A. Clarke, M. Monaco (eds.). 2009. A Marine Biogeographic Assessment of the Northwestern Hawaiian Islands. NOAA Technical Memorandum NOS NCCOS 84. Prepared by NCCOS's Biogeography Branch in cooperation with the Office of National Marine Sanctuaries Papahanaumokuakea Marine National Monument. Silver Spring, MD. 363 pp.

Example citation for an individual chapter (example of Oceanographic and Physical Setting chapter):

Desch, A., T. Wynne, R. Brainard, A. Friedlander, J. Christensen. 2009. Oceanographic and Physical Setting. pp. 17-63. In: Friedlander, A., K. Keller, L. Wedding, A. Clarke, M. Monaco (eds.). 2009. A Marine Biogeographic Assessment of the Northwestern Hawaiian Islands. NOAA Technical Memorandum NOS NCCOS 84. Prepared by NCCOS's Biogeography Branch in cooperation with the Office of National Marine Sanctuaries Papahanaumokuakea Marine National Monument. Silver Spring, MD. 363 pp.

Acknowledgements

Project funding was provided by the Office of National Marine Sanctuaries Papahanaumokuakea Marine National Monument, the National Centers for Coastal Ocean Science and the Coral Reef Conservation Program.

The completion of this document would not have been possible without the participation of the people recognized below. Their efforts to compose, format, review and edit the document are very much appreciated. Particular recognition and thanks is extended to Jamison Higgins for her assistance with the layout and production of this publication.

In addition to chapter authors, the editors would like to acknowledge the following contributors and reviewers:
George "Bud" Antonelis, Jay Barlow, Jamison Gove, Francine Fiust, Sarah Hile, David Hyrenbach, John Klavitter, Kevin McMahon, Gustav Paulay, Audrey Rivero, Jenny Waddell, Susan White and Lee Ann Woodward.

For more information

For more information about this report, please contact CCMA's Biogeography Branch Chief Mark Monaco Ph.D, at (301) 713-3028 or visit http://ccma.nos.noaa.gov/about/biogeography/.

Cover

The covers were designed and created by Gini Kennedy (NOAA). Cover photos by James Watt (NOAA), James Maragos (U.S. Fish and Wildlife Service) and the Hawaii Volcano National Park.

Mention of trade names or commercial products does not constitute endorsement or recommendation for their use by the United States government.

NMFS Honolulu Library
00000000005999

A Marine Biogeographic Assessment of the Northwestern Hawaiian Islands

Prepared for NOAA's Office of National Marine Sanctuaries (ONMS)
Papahanaumokuakea Marine National Monument

Biogeography Branch
Center for Coastal Monitoring and Assessment (CCMA)
National Centers for Coastal Ocean Science (NCCOS)
NOAA's National Ocean Service
1305 East West Highway (SSMC-IV, N/SCI-1)
Silver Spring, MD 20910
USA

NOAA Technical Memorandum NOS NCCOS 84

March 2009

Editors
Alan Friedlander, CCMA Biogeography Branch
Kaylene Keller, ONMS Papahanaumokuakea Marine National Monument
Lisa Wedding, CCMA Biogeography Branch; University of Hawaii at Manoa
Alicia Clarke, CCMA Biogeography Branch
Mark Monaco, CCMA Biogeography Branch

DEPARTMENT OF COMMERCE • UNITED STATES OF AMERICA

National Oceanic and Atmospheric Administration	National Ocean Service
Mary M. Glackin Deputy Under Secretary	John H. Dunnigan Assistant Administrator

Table of Contents

Executive Summary i

Chapter 1: Introduction **1**
Alan Friedlander, Kaylene E. Keller and Mark Monaco

Background 1
The Northwestern Hawaiian Islands Biogeographic Assessment 2
The Region's Unique Natural Environment 6
Major Taxa of Marine Resources 8
History of Use and Management 10
References 12

Chapter 2: Oceanographic and Physical Setting **17**
Arthur Desch, Timothy Wynne, Russell Brainard, Alan Friedlander and John Christensen

Introduction 17
Regional Summary 18
Ocean Remote Sensing Analysis: Data and Methods 22
Ocean Remote Sensing Analysis: Results 26
Existing Data Gaps 39
Conclusions 39
Appendix I: Sea Surface Temperature Time Series Plots 41
Appendix II: Chlorophyll Time Series Plots 51
References 61

Chapter 3: Geology and Benthic Habitats **65**
Jonathan Weiss, Joyce Miller, Emily Hirsch, John Rooney, Lisa Wedding and Alan Friedlander

Introduction and Origin 65
Benthic Habitat Mapping 69
Existing Data Gaps 101
References 102

Chapter 4: Benthic Communities **105**
James Maragos, Jean Kenyon, Greta Aeby, Peter Vroom, Bernardo Vargas-Angel, Russell Brainard, Lisa Wedding, Alan Friedlander, Jacob Asher, Brian Zgliczynski and Daria Siciliano

Introduction 105
Corals 105
Algae 139
Invertebrates 145
Existing Data Gaps 148
Appendix 150
References 152

Chapter 5: Fishes **155**
Alan Friedlander, Edward DeMartini, Lisa Wedding and Randy Clark

Biogeography of Fishes 155
Latitudinal Affinities Among Fishes 161
General Fish Assemblage Structure 165
Existing Data Gaps 187
References 188

Chapter 6: Marine Protected Species 191
Charles Littnan, Marie (Chapla) Hill, Stacy (Kubis) Hargrove, Kaylene E. Keller and Angela D. Anders

Introduction 191
Cetaceans 192
Pinnipeds 211
Marine Turtles 221
Existing Data Gaps 228
References 229

Chapter 7: Seabirds 235
Kaylene E. Keller, Angela D. Anders, Scott A. Shaffer, Michelle A. Kappes, Beth Flint and Alan Friedlander

Introduction 235
Procellariiformes (Albatrosses, Petrels and Shearwaters) 240
Pelecaniformes (Boobies, Frigatebirds and Tropicbirds) 249
Charadriiformes (Terns and Noddies) 256
Population Status and Trends 263
Existing Data Gaps 271
References 272

Chapter 8: Nonindigenous and Invasive Species 275
Kevin See, Scott Godwin and Charles Menza

Introduction 275
Marine Algae 278
Invertebrates 280
Fishes 285
Management 287
Existing Data Gaps 287
References 288

Chapter 9: Connectivity and Integrated Ecosystem Studies 291
Alan Friedlander, Donald Kobayashi, Brian Bowen, Carl Meyers, Yannis Papastamatiou, Edward DeMartini, Frank Parrish, Eric Treml, Carolyn Currin, Anna Hilting, Jonathan Weiss, Chris Kelley, Robert O'Conner, Michael Parke, Randy Clark, Rob Toonen and Lisa Wedding

Introduction 291
Large-Scale Population Connectivity Models from Ocean Currents 291
Essential Fish Habitat 316
Trophic Relationships: Stable Isotope Composition of Primary Producers and Consumer Organisms 320
Food Web Models 324
Existing Data Gaps 326
References 328

Chapter 10: Management Concerns and Responsibilities 331
Kaylene E. Keller, Angela D. Anders, Ann Mooney, Randall Kosaki, Malia Chow and Mark Monaco

Introduction 331
Background 331
World Heritage Nomination 333
Management of Protected Species 334
Management of Threats to the Ecosystem 336
Management of Human Impacts 349
Monument Permit Applications and Permit Issuance 351
Future Directions and Implications for a Biogeographic Assessment to Support Hawaiian Archipelago Spatial Management 359
References 361

EXECUTIVE SUMMARY

The mission of NOAA's Office of National Marine Sanctuaries (ONMS) is to serve as the trustee for a system of marine protected areas, to conserve, protect and enhance biodiversity. To assist in accomplishing this mission, the ONMS has developed a partnership with NOAA's Center for Coastal Monitoring and Assessment's Biogeography Branch (CCMA-BB) to conduct biogeographic assessments of marine resources within and adjacent to the marine waters of NOAA's National Marine Sanctuaries (Kendall and Monaco, 2003).

Biogeography is the study of spatial and temporal distributions of organisms, their associated habitats, and the historical and biological factors that influence species' distributions. Biogeography provides a framework to integrate species distributions and life history data with information on the habitats of a region to characterize and assess living marine resources within a sanctuary. The biogeographic data are integrated in a Geographical Information System (GIS) to enable visualization of species' spatial and temporal patterns, and to predict changes in abundance that may result from a variety of natural and anthropogenic perturbations or management strategies (Monaco et al., 2005; Battista and Monaco, 2004).

Defining biogeographic patterns of living marine resources found throughout the Northwestern Hawaiian Islands (NWHI) was identified as a priority activity at a May 2003 workshop designed to outline scientific and management information needs for the NWHI (Alexander et al., 2004). NOAA's Biogeography Branch and the Papahanaumokuakea Marine National Monument (PMNM) under the direction of the ONMS designed and implemented this biogeographic assessment to directly support the research and management needs of the PMNM by providing a suite of spatially-articulated products in map and tabular formats. The major findings of the biogeographic assessment are organized by chapter and listed below.

The NWHI are home to a wide variety of ecosystems and living marine resources. Photos: J. Maragos.

Oceanography

- Sea surface temperature (SST) analyses suggest three latitudinal subunits:
    - North – Kure, Midway, Pearl and Hermes – temperature range 20-27 °C, among the largest variation in any coral reef ecosystem;
    - Middle – Lisianski to Gardner; and
    - Southern – French Frigate Shoals to Nihoa, average temperature range 23-27 °C.
- SST analysis suggest there may have been bleaching events in 1987 and 1991 based on temperature anomalies >1 °C during warm period (August-September).
- Sea surface fronts or eddies are active in the northern region from December to April with a peak in March. Few fronts are found in the southern portion and during mid-summer, fronts retreat to the north.
- Low productivity ocean water is increasing worldwide due to climate change and this water has reached the Hawaiian archipelago with major implications for ecosystem productivity.

Geology and Benthic Habitats

- Only 50% of shallow water habitats (0-30 m) have been mapped with more than one-half of this habitat consisting of hardbottom.
- Nearly complete high resolution bathymetric coverage from 3 to 3,000 m exists for Kure, Midway, Pearl and Hermes, Brooks Bank and French Frigate Shoals.
- Upchain islands (Kure, Midway, Pearl and Hermes and Lisianski) have steeper slopes compared to downchain islands. The highest rugosity (complexity) derived from multibeam data was at Pearl and Hermes.

Benthic Communities

- There are approximately 80 morphologically distinct coral "species" in the NWHI, and about 35 are likely to be endemic (44%). This represents some of the highest endemism of any coral assemblage found on earth. More than 25 NWHI species are still undescribed or unidentified, and once type specimens are collected and examined morphologically and genetically, then final determinations can be made on which corals are new species and possible endemics. Notwithstanding efforts to date, NWHI explorations are still inadequate, and it is likely that additional undescribed coral species will be encountered in the future.
- The highest species richness was observed at French Frigate Shoals and reflects optimal conditions for coral growth (optimal temperature, low wave exposure, large open atoll)
- Coral cover, based on tow board data, was 8% overall. Lisianski (19%) and Maro (15%) had the highest cover while Midway (2%) had the lowest. Coral cover on hard bottom only was highest at Maro (39%) and Lisianski (37%).
- No significant differences were found in coral cover at permanent locations between 2002 and 2006.
- Disease prevalence is low overall, <1%.
- Algal diversity is similar across the chain but brown algae are more abundant at the northern end of the chain (Midway and Kure). Algal endemism was calculated at 11% for French Frigate Shoals, and 7% for Gardner Pinnacles, however recent molecular evidence coupled with more detailed morphological observations are finding that a large percentage of the Hawaiian algal flora are likely incorrectly identified and may be species new to science.

Fishes

- Endemism based on numbers is 52% and 21% based on species richness.
- Fish assemblages showed latitudinal affinities with more subtropical and temperate species found to the north and more tropical species to the south. The major faunal break occurs around Maro and Laysan.
- Midway and Kure have a distinct fish assemblage based on biomass as does Nihoa and Mokumanamana. These distinct assemblages at the extremes of the chain are likely the result of temperature and habitat.
- Grey reef sharks are more common downchain while Galapagos sharks are more common to the north. The transition occurred around Gardner and Maro.
- Ranking of fish assemblages (based on endemism, species richness, number of individuals, biomass, apex predator biomass and recruitment) show Pearl and Hermes with the highest rank, followed by Midway, and French Frigate Shoals, respectively.

Protected Species

- Fifteen cetacean species have been observed within the Monument boundaries. This group of organisms has not been well studied in the NWHI and it may represent an important area for these species.

- Hawaiian monk seals have shown dramatic declines since the late 1990s but these declines differ among locations and for various reasons. French Frigate Shoals currently supports the largest colony but has also shown the steepest decline (75% since 1989) with low juvenile survival. Laysan and Lisianski have remained fairly constant over the past decade. Pearl and Hermes is the only location to have shown an increase in the past 10 years. Low population numbers at Midway and Kure are likely the result of long histories of human disturbance.
- Green turtle populations continue to increase in the NWHI, representing a major conservation success story. French Frigate Shoals accounts for over 90% of the nesting population with Laysan, Lisianski, and Pearl and Hermes accounting for the remainder. Despite extensive potential beach nesting habitat at Midway and Kure, limited nesting has been observed at Midway and none at Kure.

Seabirds

- Twenty-two species of seabirds exist in the NWHI, representing one of the most important locations for seabirds in the tropics. Despite the importance of this region, long-term data collection has been restricted to a few species at a limited number of locations.
- Foraging areas range from only a few kilometers for some species (e.g. Little Terns) to over 1,000 km for species like the Laysan Albatross. Wide ranging species will require cooperative management at national and international levels.
- Changes in SST and primary production will result in changes in seabird populations over time and monitoring of these populations will be important to better understand the impacts of climate change.

Nonindigenous and Invasive Species

- The presence of invasive species is currently concentrated in harbors and when man-made objects are present.
- The blueline snapper (Taape) have spread from Oahu in 1958 to Midway in 1992, a distance of 1,180 nmi and observations at other islands in the chain show during this time period show a rate of spread of about 18-70 nmi/yr. On the other hand the Peacock grouper (Roi) has only made it as far as French Frigate Shoals or about 5-17 nmi/year.
- The current presence of invasive species is low but data are limited, particularly at deeper depths and more systematic sampling is currently being implemented.

Connectivity and Integrated Ecosystem Studies

- Advection-diffusion ocean current models show Kure, Midway, and Pearl and Hermes strongly connected. Scale of dispersal is on the order of 50-150 km.
- High-resolution ocean current data and computer simulation showed that for organisms with short larval duration (15 days – e.g., corals and some invertebrates), a narrow transitional region from Kauai to Nihoa included settlers from both the Main Hawaiian Islands (MHI) and NWHI. For typical fish larvae (45 day larval duration) there appeared to be little exchange between the NWHI and the MHI north of French Frigate Shoals. For the few organisms with longer larval durations (eg., Bottomfishes, lobster) nearly all regions of the MHI have at least some NWHI settlers where as most of the NWHI is self-seeding.
- Giant trevally (ulua) and jobfish (uku) show no inter-atoll movement over a several year period. They congregate around channels and reef passes and make seasonal, within-atoll movements to spawn.
- Genetic connectivity for opihi, the Hawaiian endemic limpet, between the MHI and NWHI is too low (less than three migrants per generation) to replenish MHI stocks and one species is not even found in the NWHI.

- Barriers to genetic dispersal occur between Pearl and Hermes and Midway, as well as between Niihau and French Frigate Shoals for some species however closely related species with similar ecology and reproductive biology have dramatically different patterns of connectivity.
- Potential bottom fish habitat was calculated among islands based on depth (100-400 m), slope (>20%), and hardness using available mapping data. Kure (31%) and Maro (30%) had the greatest percentage of potential bottom fish habitat to total area mapped. These results may indicate areas with high populations and therefore greater replenishment potential for other locations. These results may also be useful in identifying monk seal forage habitat.
- Stable isotope analysis indicates that benthic algae provide the majority of the trophic support for apex predators and the entire system consists of short (three to four trophic levels above primary production) food chain. These results are very consistent with the Ecopath model estimates of food web supporting fisheries production in the NWHI.

Management

- The complex meta-population dynamics observed in the NWHI requires a better understanding of how these populations replenish themselves and how they connect to other areas.
- The results show some areas of strong linkage and others with clear breaks in connectivity. This will require zoning and other spatial management tools to maintain ecosystem function.
- Current and future changes in the environment as a result of climate change will require more comprehensive assessment and monitoring along with the ability to respond in a timely manner to mitigate potential negative impacts to the ecosystem.
- The data gaps identified in the report (e.g., shallow-water maps, cetaceans, seabirds, deeper habitats, etc.) need to be addressed in order to have a better understanding of the entire ecosystem.
- A biogeographic assessment that integrates the MHI and NWHI would better help to explain ecosystem connectivity and processes.

For questions or more information, please visit http://ccma.nos.noaa.gov/about/biogeography/ or contact:

Mark E. Monaco, Ph.D.
Biogeography Branch Chief
NOAA/NCCOS/CCMA
1305 East West Highway, N/SCI1
Silver Spring, MD 20910
Email: mark.monaco@noaa.gov

Alan M. Friedlander, Ph.D.
USGS Hawaii Cooperative Fishery Research Unit
Department of Zoology
University of Hawaii
2538 The Mall
Honolulu, HI 96822
Email: alan.friedlander@hawaii.edu

REFERENCES

Alexander, C.A., S.R. Gittings, R. Kosaki, and M.S. Tartt. 2004. Information needs for conservation science and management of the Northwestern Hawaiian Islands: a product of the I ke amio o na wa'a workshop. National Oceanic and Atmospheric Administration, Marine Sanctuaries Division. 31 pp. & app.

Battista, T.A. and M.E. Monaco. 2004. Geographic information systems application in coastal marine fisheries. Pages 189-208 In: W.L. Fisher and R.J. Rahel, editors, Geographic information systems in fisheries. American Fisheries Society, Bethesda, MD.

Kendall, M.S., and M.E. Monaco. 2003. Biogeography of the National Marine Sanctuaries: A Partnership between the National Marine Sanctuary Program and the National Centers for Coastal Ocean Science Biogeography Program. Unpublished Report. 15 pp.

Monaco, M., Kendall, M., Higgins, J., Alexander, C., and Tartt, M., (2005) Biogeographic assessments of NOAA National Marine Sanctuaries: The integration of ecology and GIS to aid in marine management boundary delineation and assessment, in Wright, D.J. and Scholz, A.J. (Eds.), "Place Matters: Geospatial Tools for Marine Science, Conservation, and Management in the Pacific Northwest," Corvallis, OR: Oregon State University Press, 2005.

Introduction

Alan Friedlander[1,2], Kaylene E. Keller[3] and Mark Monaco[1]

BACKGROUND

The mission of NOAA's Office of National Marine Sanctuaries (ONMS) is to serve as the trustee for a system of marine protected areas, to conserve, protect and enhance biodiversity. To assist in accomplishing this mission, the ONMS has developed a partnership with NOAA's Center for Coastal Monitoring and Assessment's Biogeography Branch (CCMA-BB) to conduct biogeographic assessments of marine resources within and adjacent to the marine waters of NOAA's National Marine Sanctuaries (Kendall and Monaco, 2003).

Biogeography is the study of spatial and temporal distributions of organisms, their associated habitats, and the historical and biological factors that influence species' distributions. Biogeography provides a framework to integrate species distributions and life history data with information on habitats of a region to characterize and assess living marine resources within a marine protected area. The biogeographic data are integrated in a Geographical Information System (GIS) to enable visualization of species' spatial and temporal patterns and to predict changes in abundance that may result from a variety of natural and anthropogenic perturbations or management strategies (Monaco et al., 2005; Battista and Monaco, 2004). The complexity of products from biogeographic analysis range from simple species distribution maps of a particular habitat, to more complex products that combine single data layers to create maps of biodiversity or habitat complexity (NOAA, 2003b; Pittman et al., 2007). The biogeographic assessment approach was developed by the CCMA-BB in consultation with the ONMS in 2003 (Kendall and Monaco, 2003; Monaco et al., 2005; Figure 1.1).

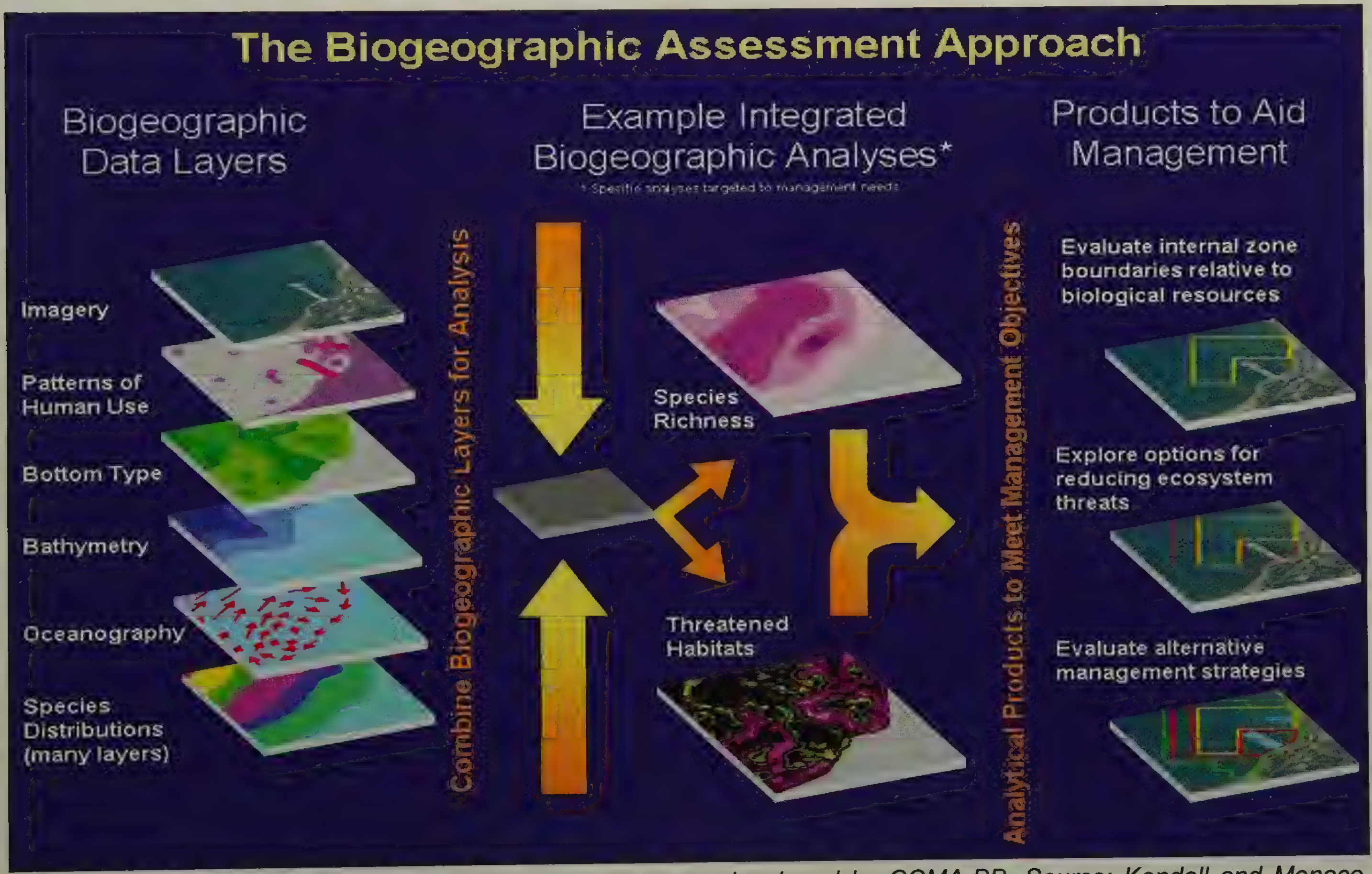

The Biogeographic Assessment Approach
Biogeographic Data Layers
Example Integrated Biogeographic Analyses*
* Specific analyses targeted to management needs
Products to Aid Management
Imagery
Patterns of Human Use
Bottom Type
Bathymetry
Oceanography
Species Distributions (many layers)
Combine Biogeographic Layers for Analysis
Species Richness
Threatened Habitats
Analytical Products to Meet Management Objectives
Evaluate internal zone boundaries relative to biological resources
Explore options for reducing ecosystem threats
Evaluate alternative management strategies

Figure 1.1. Generalized biogeographic assessment process developed by CCMA-BB. Source: Kendall and Monaco, 2003.

---

[1] NOAA/NOS/NCCOS/CCMA Biogeography Branch
[2] The Oceanic Institute
[3] NOAA/NOS/ONMS/Papahanaumokuakea Marine National Monument

Typically a biogeographic assessment is comprised of the three primary activities: 1) compile individual biogeographic data layers, 2) perform integrated biogeographic analyses, and 3) develop products to aid in management (Figure 1.1). A key tool used to develop and implement the assessment is the use of GIS technology which aids in data compilation, spatial analyses, and visualization of results to support place-based management needs (Battista and Monaco, 2004). The assessment process shown in Figure 1.1 is based on geospatial and temporal analyses of existing physical and biological data and has resulted in many spatially-oriented products that help managers understand how ecosystems function. Often biogeographic analyses focus on determining the strength of coupling between habitats and species and defining discrete areas of biological significance (NOAA, 2003; NOAA, 2005; Monaco et al., 2005).

Defining biogeographic patterns of living marine resources found throughout the Northwestern Hawaiian Islands (NWHI) was identified as a priority activity at a May 2003 workshop designed to define scientific and management information needs for the NWHI. NOAA's Biogeography Branch and the Papahanaumokuakea Marine National Monument (PMNM) under the direction of the ONMS designed and implemented this biogeographic assessment to directly support the research and management needs of the Monument, such as, minimizing impacts of permitted research activities on NWHI marine resources. Successful implementation of this assessment required cooperation and participation with many federal, state, academic and private sector partners. Without participation of key partners, such as NOAA's Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division, the University of Hawaii, the University of Miami, the State of Hawaii's Division of Aquatic Resources, and the U.S. Fish and Wildlife Service, the biogeographic assessment would have not been completed.

THE NORTHWESTERN HAWAIIAN ISLANDS MARINE BIOGEOGRAPHIC ASSESSMENT

In an effort to provide further protection of the NWHI, the Monument was created by Presidential proclamation on June 15, 2006. The Co-Trustees for the Monument are NOAA, the Department of the Interior and the state of Hawaii. This biogeographic assessment was designed to support the Monument's scientific and management needs based on historical, recent and planned research and monitoring studies within the Monument (Table 1.1). The assessment has resulted in a suite of spatially-articulated products for use by the Monument

Table 1.1. The monitoring programs that are currently collecting data in the NWHI.

MONITORING PROGRAM	OBJECTIVES	YEAR EST.	FUNDING	AGENCIES
Fishery monitoring and economics program	Fisheries catch and effort statistics	1948	NOAA	PIFSC, DAR
Marine turtle research program	Monitor selected sea turtle breeding sites	1973	NOAA, USFWS	USFWS, PIFSC
Seabird monitoring	Monitoring selected nesting seabird species	1978	USFWS	USFWS, PIFSC
Fishery independent lobster monitoring	Monitor lobster using fisheries-independent sampling	1983	NOAA	PISSC
Marine mammal research program	Monitor and assess subpopulations	1985	NOAA	PIFSC, USFWS
Marine debris program	Rates of marine debris accumulation	1996	NOAA	CRED, UH, USFWS, DAR, USGS
Reef assessment and monitoring program	Monitor and assess reef communities through integrated ecosystem science	2000	CRCP	CRED, USFWS, NMSP, DAR, numerous collaborators
Oceanography & water quality program	Physical and chemical oceanographic conditions and processes influencing reef health.	2000	NOAA	PIFSC-CRED, UH
Coral monitoring	Monitoring corals at permanent sites	2000	HCRI, USFWS	USFWS, PIFSC-CRED
Connectivity and ecosystem health	Examine connectivity, ecosystem health, and genetic structure	2005	NMSP	HIMB

Abbreviatons: CRCP – NOAA's Coral Reef Conservation Program; CRED - Coral Reef Ecosystem Division; DAR - Hawaii Division of Aquatic Resources, Department of Land and Natural Resources; HCRI - Hawaii Coral Reef Initiative; HIMB - Hawaii Institute of Marine Biology; NMSP - National Marine Sanctuary Program; NOS - National Ocean Service; PIFSC - Pacific Islands Fisheries Science Center; UH - University of Hawaii; USGS – U.S. Geological Survey and its partners to support ecosystem-based management and the long-term, comprehensive protection and conservation of the marine resources of the NWHI. Results of this assessment will also support the adaptive management process, identify gaps in information and direct research priorities.

Project Objectives

The biogeographic assessment of the NWHI contributes greatly toward ecosystem-based management of the marine resources of the NWHI. The study is broad in scope and includes characterization of the physical and biological environments (e.g., oceanography, habitats) that structure the spatial and temporal distribution of living marine resources within and adjacent to the Monument boundaries. The objectives of the study were:

1. Identify and synthesize relevant biological, physical and socioeconomic data sets for the study area. Organize the data in a common spatial framework within a GIS.
2. Conduct a marine biogeographic analysis of available data to identify important ecological linkages and biologically significant regions and time periods, based on species distributions, abundance, associated habitats and their ecological function.

The objectives were addressed using the biogeographic assessment process (Figure 1.1) and resulted in a synthesis of multiple data sets that range across the NWHI to enable characterization of the biological and physical environment that structures the biogeographic patterns in space and time of living marine resources found within the Monument. The data, analyses and supporting information are linked using statistical and GIS tools to visualize the location of significant biological areas or "hot spots." There were many alternative approaches to analyze and organize the biological, physical and habitat data compiled for this assessment. However, only a limited number of analytical options were selected based on reviewer's comments on the project work plan and technical review meetings. These key analyses are presented in this document. A critical step in assessment process was the extensive effort to have data, analytical approaches and results peer reviewed. Initial results from the suite of analyses were presented to experts on NWHI marine ecosystem, as well as to the originators of the data sources in an attempt to improve the analyses. The role of expert review and input has been considerable, and the contributions made by experts have significantly enhanced the study results.

The use of the GIS enabled species-specific data, such as distribution and abundance data or community metrics (e.g., species richness), to be directly linked to specific areas or habitats they correspond with across the study area. The GIS also facilitated integration of multiple data types and sources into a common spatial and temporal framework (Gill et al., 2001).

The chapters that follow focus on the spatial and temporal distribution data and analyses from the assessment. The report is organized by introducing the geology, habitats and oceanographic characteristics of the NWHI and then followed by the biogeography of living marine resource found within and adjacent to the Monument (Miller et al., 2003; Maragos et al., 2004). The Connectivity and Integrated Ecosystem Studies chapter addresses combinations of the individual biogeographic data layers to characterize the Monument based on the integration of physical and biological data, including ecological and genetic connectivity that define the PMNM ecosystem. Finally, the Management Concerns and Responsibilities chapter focuses on the management of the Monument including the management structure, protected species occurring within the Monument, the management of human activities and the greatest potential threats to the region. Below are brief summaries that characterize the PMNM ecosystem and are discussed in greater detail in individual sections.

Region of Interest

The remoteness and protective status of the NWHI has minimized reef degradation suffered by many other coral reefs around the world (Friedlander et al., 2005, 2008; Grigg et al., 2008). The NWHI consist of small islands, atolls, submerged banks, and reefs, that stretch for more than 2,000 km northwest of the high windward Main Hawaiian Islands (MHI; Figure 1.2). The majority of the islets and shoals remain uninhabited, although Midway, Kure, Laysan Island and French Frigate Shoals have all been occupied for extended periods over

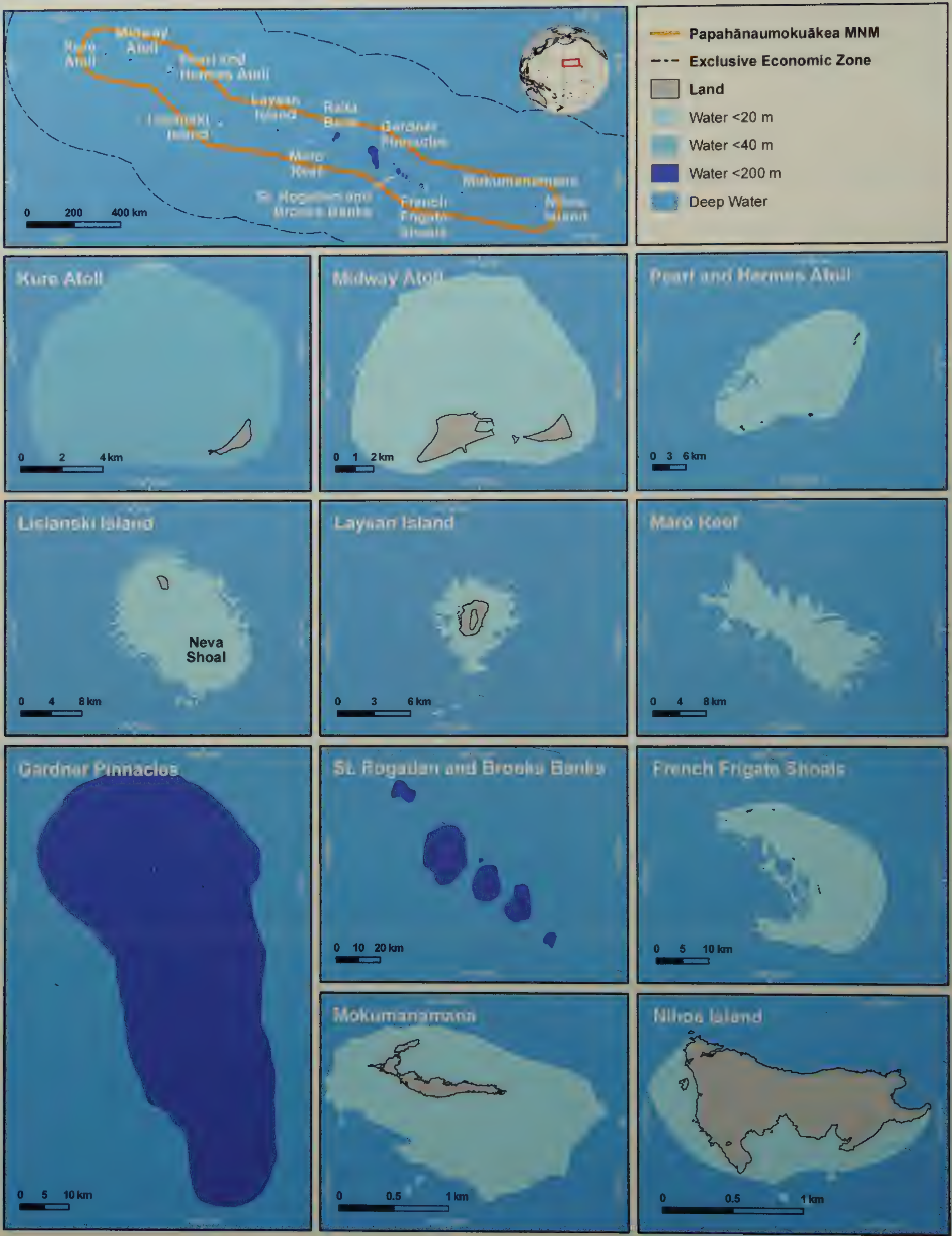


Figure 1.2. The Northwestern Hawaiian Islands, which extend across the north central Pacific, represent a vast, remote coral ecosystem that has been subjected to relatively minimal anthropogenic impacts. Map: K. Buja.

the last century by various government agencies. The inaccessibility, limited fishing and lack of other human activities in the NWHI have resulted in minimal anthropogenic impacts (Friedlander et al., 2005, 2008), therefore providing a unique opportunity to assess how a "natural" coral reef ecosystem functions in the absence of major localized human intervention and contrast these with anthropogenic influences experienced in the MHI and other comparable ecosystems (Friedlander and DeMartini, 2002; Grigg et al., 2008).

One of the most striking and unique components of the NWHI ecosystem is the abundance and dominance of large apex predators such as sharks and jacks (Figure 1.3; Hobson, 1984; Parrish et al., 1985; Friedlander and DeMartini, 2002), which exert a strong top-down control on the ecosystem (DeMartini et al., 2005; DeMartini and Friedlander, 2006) and have been depleted in most other locations around the world (Meyer and Worm, 2003; 2005). The NWHI flora and fauna include a large percentage of species that are endemic to the Hawaiian Islands, which are recognized for having some of the highest marine endemism in the world (Kay and Palumbi, 1987; Jokiel, 1987; Randall, 1998; Randall, 2007). Some of these endemics are dominant components of the community, resulting in a unique ecosystem that has extremely high conservation value and has identified Hawaii as an important global biodiversity hot spot (DeMartini and Friedlander, 2004; Maragos et al., 2004). The few alien species known from the NWHI are restricted to the anthropogenic impacted habitats of Midway Atoll and French Frigate Shoals (Friedlander et al., 2005, 2008; Godwin et al., 2006). Disease levels in corals in the NWHI are much lower than those reported from other locations in the Indo-Pacific (Aeby, 2006).

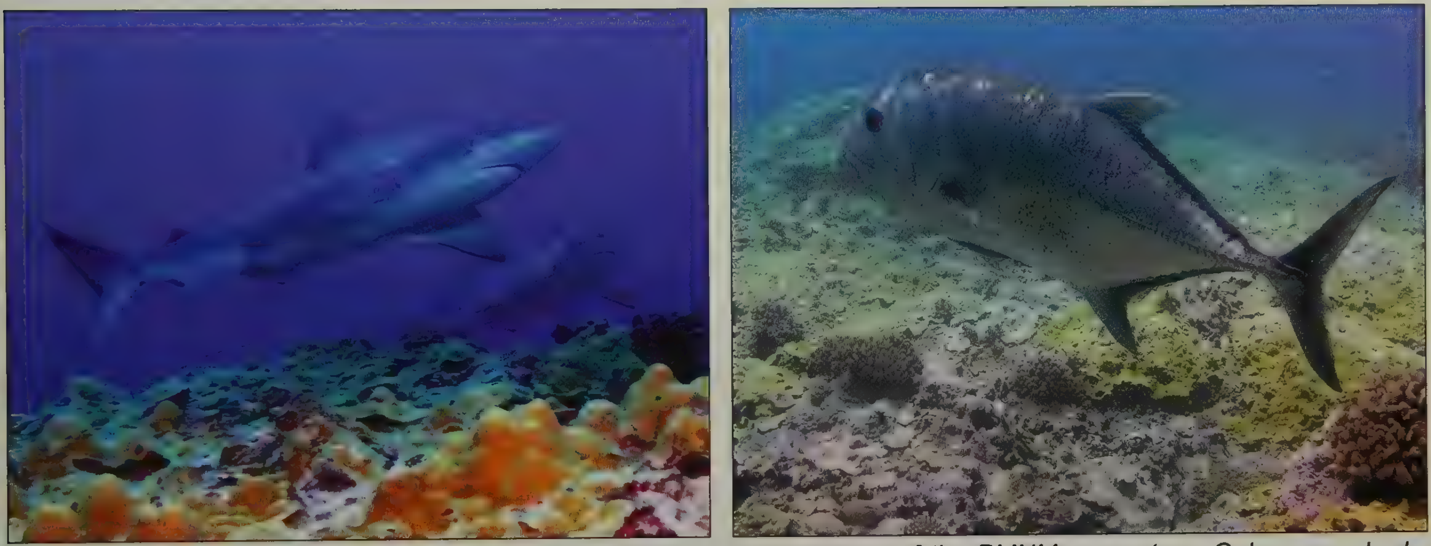
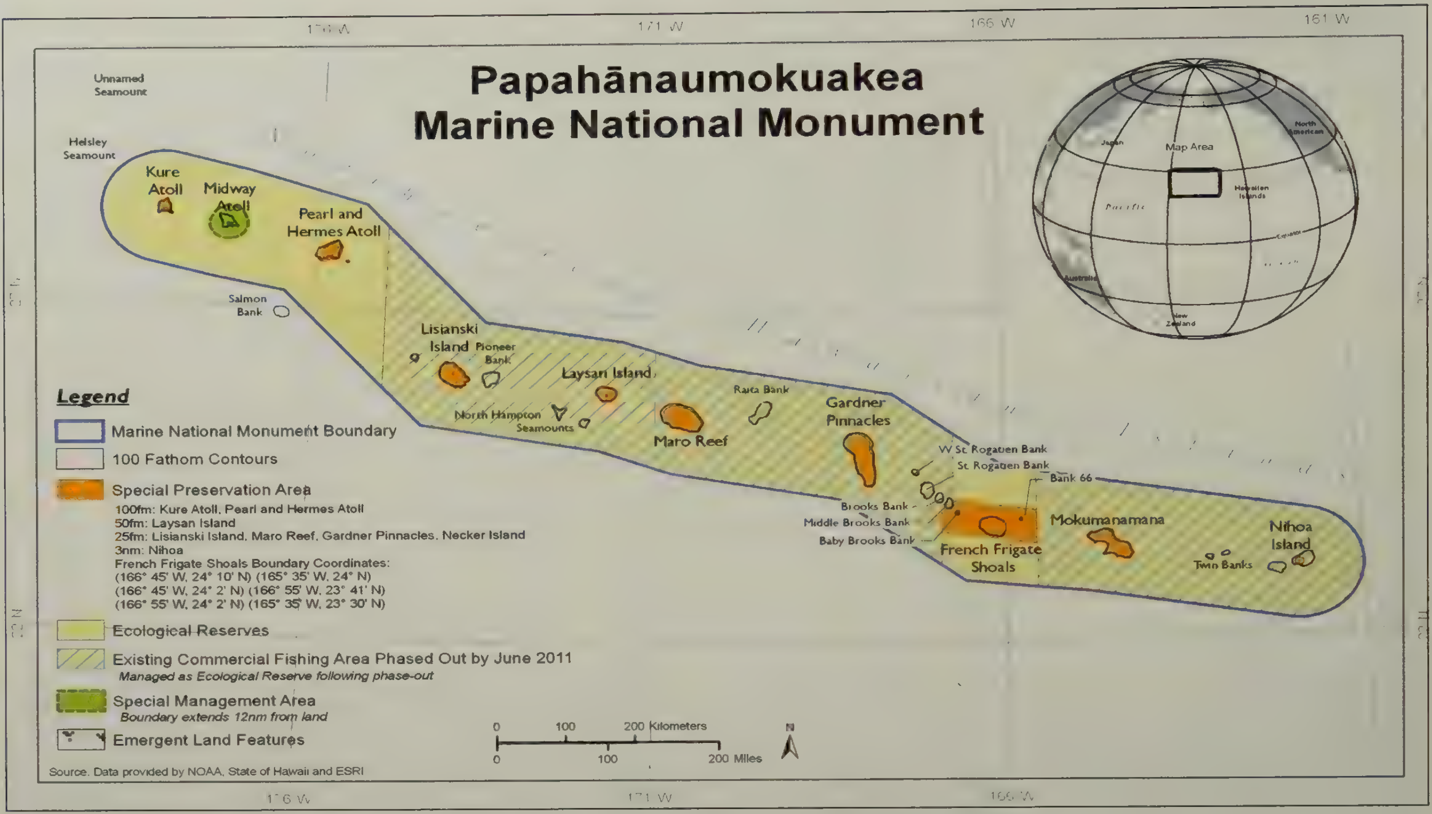


*Figure 1.3. Apex predators are a conspicuous and important component of the PMNM ecosystem. Galapagos sharks (*Carcharhinus galapagensis*; left) at Maro Reef and giant trevally (*Caranx ignobilis*; right), known as ulua in Hawaii, from French Frigate Shoals. Photos: J. Maragos.*

The NWHI represent important habitat for a number of threatened and endangered species. The Hawaiian monk seal is one of the most critically endangered marine mammals in the U.S. (approximately 1,200 individuals) and depends almost entirely on the islands of the NWHI for breeding and the surrounding reefs for sustenance (Antonelis et al., 2006). Over 90% of all sub-adult and adult Hawaiian green sea turtles found throughout Hawaii inhabit the NWHI (Balazs and Chaloupka, 2006). Additionally, seabird colonies in the NWHI constitute one of the largest and most important assemblages of seabirds in the world (USFWS, 2005).

On June 15, 2006, President George W. Bush designed the NWHI as a Marine National Monument, the largest no-take marine conservation areas on earth, through the signing of Proclamation 8031. In March 2007, First Lady Laura Bush renamed the Monument the Papahanaumokuakea Marine National Monument on behalf of the President. The Monument encompasses nearly 225,300 km^2 of ocean and includes all the islands, atolls, shoals and banks from Nihoa Island to Kure Atoll (Figure 1.4). The unique predator-dominated trophic structure, the dominance by large numbers of endemic species, and the occurrence of a number of threatened and endangered species makes the NWHI an ecosystem of global significance.



Source. Data provided by NOAA, State of Hawaii and ESRI

Figure 1.4. Papahanaumokuakea Marine National Monument boundaries. Map: PMNM.

THE REGION'S UNIQUE NATURAL ENVIRONMENT

The NWHI are influenced by a dynamic environment that includes large annual water temperature fluctuations, seasonally high wave energy, and strong inter-annual and inter-decadal variations in ocean productivity (Grigg, 1983; Polovina et al., 2001). As a result of these influences and the general absence of human interference, natural stressors play an important role in the structure of the NWHI ecosystem (Friedlander et al., 2005). Large swell events generated every winter commonly produce waves up to 10-12 m in height, which limits the growth and abundance of coral communities, and leads to species and growth forms that are adapted to these dynamic high wave energy environments (Grigg et al., 2008).

Compared with most reef ecosystems around the globe, the large annual fluctuation of sea surface temperatures (SSTs; >10°C) found at the northernmost atolls of the NWHI is extremely high. Cooler water temperatures to the north restrict the growth and distribution of a number of coral species (Grigg, 1983), and the biogeographic distribution of many fish species in the NWHI is influenced by differences in water temperatures along the archipelago (DeMartini and Friedlander, 2004; Mundy, 2005).

Large-Scale Biogeographic Regions

The NWHI is set in a dynamic oceanographic and meteorological regime in the northern/central subtropical region of the Pacific Ocean (Figure 1.5). The NWHI archipelago extends such a great distance that the two opposite ends of the chain often experience somewhat different oceanographic and meteorological conditions (Table 1.2). The NWHI are not usually impacted by tropical storms but do experience large boreal winter wave events that assist in shaping the ecosystem. The boundary between the nutrient-poor, or oligotrophic, surface waters of North Pacific Subtropical Gyre and the nutrient-rich, or eutrophic, surface waters of the North Pacific Subpolar Gyre is frequently in the NWHI region (Leonard et al., 2001). This front shifts 15° (between 30° and 45°N) seasonally (Polovina et al., 2001), reaching far enough south in the winter to encompass the northern most three atolls (Kure, Midway, and Pearl and Hermes). The southern extension of this front into the NWHI region, migrating on interannual and decadal time scales, brings colder and nutrient rich waters that are likely important to the productivity and ecology of these coral reef ecosystems. The location of this front also influences marine debris concentrations (Kubota, 1994), which has been shown to most severely impact the northern atolls (Boland et al., 2004; Donohue et al., 2001).

Geology and Evolutionary History

The Hawaiian Archipelago originated over a relatively stationary melting anomaly or hot spot in earth's mantle located below the floor of the Pacific Plate, which is drifting over the hot spot to the northwest at a rate of about 8 cm/yr (Figure 1.6; Grigg et al., 2008; Rooney et al., 2008). Because the plate is slowly cooling as it moves away from the hot spot, the overriding islands and other volcanic features are slowly subsiding. Beginning at Nihoa and Mokumanamana Island (approximately seven and 10 million years old, respectively) and extending to Midway and Kure Atolls (approximately 28 million years old), the NWHI represent the older portion of the emergent Hawaiian Archipelago (Grigg, 1988; Juvik and Juvik, 1998; Rooney et al., 2008).

The Hawaiian Archipelago is 3,900 km from the west coast of the U.S. mainland, 3,800 km from Japan, and over 1,000 km from the nearest island archipelago (the Line Islands). This geographic isolation of the entire Hawaiian Island chain has resulted in a large number of species that are found nowhere else on earth, and the proportion of these endemic species (>25% for most taxa) to other native species is some of the highest recorded for any tropical marine ecosystem to date. Some of these endemics are dominant components of the coral reef community, resulting in a unique ecosystem that has extremely high conservation value (DeMartini and Friedlander, 2004; Maragos et al., 2004).

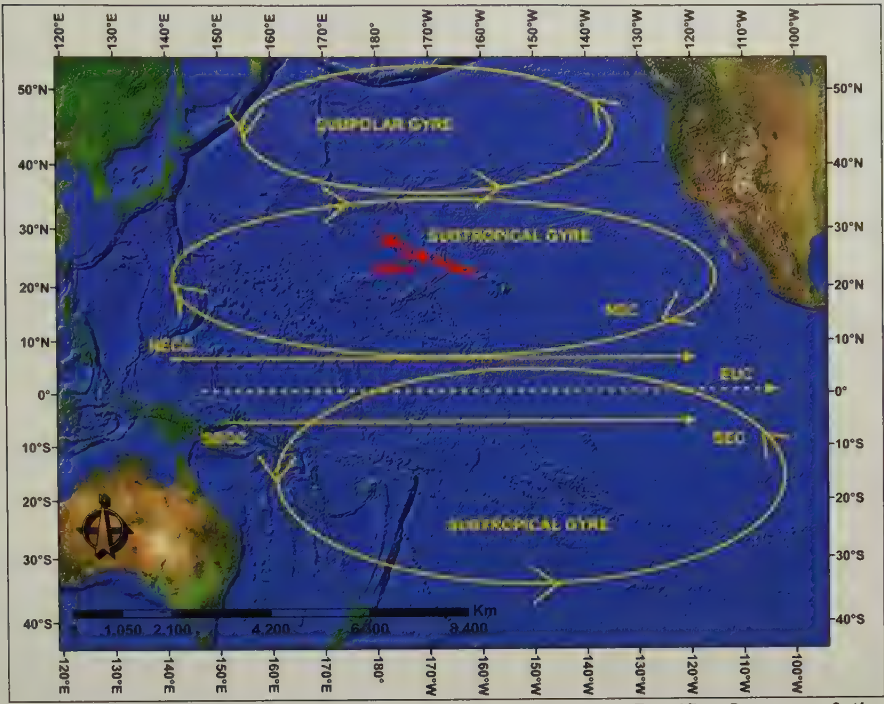


Figure 1.5. Topographic map showing location in Pacific Ocean of the Northwestern Hawaiian Islands (NWHI) and the major ocean currents in the region (North Equatorial Current (NEC, South Equatorial Current (SEC), North Equatorial Counter Current (NECC), South Equatorial Counter Current (SECC), Equatorial Under Current (EUC). Source: CRED.

Table 1.2. Coordinates and Hawaiian names of the 10 islands presented from north to south.

ISLAND	HAWAIIAN NAME	LATITUDE	LONGITUDE
Kure Atoll	Kanemilohai, Mokupapapa	28° 26'N	178° 19'W
Midway Atoll	Pihemanu	28° 14'N	177° 22'W
Pearl and Hermes Atoll	Holoikauaua	27° 51'N	175° 51'W
Lisianski Island and Neva Shoals	Papaapoho	26° 3'N	173° 58'W
Laysan Island	Kauo	25° 47'N	171° 44'W
Maro Reef	Nalukakala, Koanakoa	25° 27'N	170° 37'W
Gardner Pinnacles	Puhahonu	24° 52'N	168° 1'W
French Frigate Shoals	Mokupapapa, Kanemilohai	23° 46'N	166° 12'W
Mokumanamana Island	Mokumanamana	23° 27'N	164° 31'W
Nihoa Island	Nihoa	23° 5'N	161° 51'W

Figure 1.6. Lava flowing into the ocean off the southeast coast of the island of Hawaii. Photo: Hawaii Volcano Naitonal Park.

MAJOR TAXA OF MARINE RESOURCES

Benthic Communities

The composition and distribution of benthic communities in the NWHI reflect the interaction of numerous influences, including isolation, latitude, exposure, and the successional age of the island they inhabit. Mosaics of habitats range from coral-dominated areas to vast expanses of unconsolidated sediments such as sand and mud inhabited by a few epi-benthic fauna.

Despite their high latitude location, slightly more species of coral have been reported from the NWHI (52 species) compared with the MHI (48 species; Maragos et al., 2004), although a number of potentially new species have recently been discovered (Friedlander et al., 2008). Kure is the world's most northern atoll (28° 26'N) and is referred to as the Darwin Point, where coral growth and subsidence /erosion balance one another (Grigg, 1982). Beyond this point lies a chain of seamounts that get progressively deeper and older as they move away from a stationary melting point or hot spot in the Pacific plate located southeast of the big island of Hawaii (Grigg, 1988).

The coral assemblage in the NWHI contains a large number of endemics (approximately 30%), including at least seven species of table corals (acroporids), which are the dominant reef-building coral in the Indo-Pacific, but are absent from the MHI (Figure 1.7, Maragos et al. 2004). Coral disease is currently low in the NWHI; but increases in the frequency and intensity of bleaching events due to global warming could stress corals and make them more susceptible to disease.

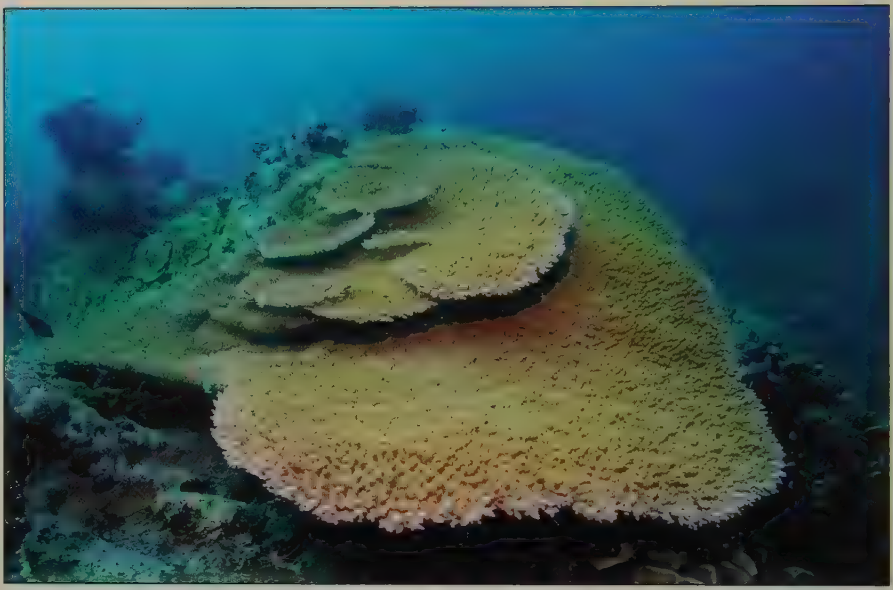


*Figure 1.7. Table coral (*Acropora cytherea*) at French Frigate Shoals. Photo: J. Watt.*

Unlike the MHI where alien and invasive algae have overgrown many coral reefs, the shallow reefs in the NWHI appear to be free of invasive algae, and high natural herbivory (grazing) results in a pristine algal assemblage. Algal diversity appears similar across the NWHI chain even though brown algae tend to be more abundant at Midway and Kure Atolls than at most other islands (Vroom and Page, 2006). The cooler SSTs found at Kure and Midway Atolls during winter months may favor a higher abundance of brown algal species. Lower abundance of green algae at Midway may result from higher herbivorous fish densities at this atoll system, suggesting possible top-down control of the benthic habitat (DeMartini and Friedlander, 2004, 2006).

The NWHI are documented to contain the highest percent cover of algal species when compared to other geographic locations throughout the U.S. tropical Pacific, and the lowest percent cover of living coral (Vroom et al., 2006). This is likely due to the subtropical location of the NWHI and cool SSTs that bathe biological communities during winter months. Despite relatively high algal populations, the NWHI remain a healthy and thriving marine ecosystem.

Fishes

A total of 457 reef and shore fishes have been reported from the MHI while 258 are documented from Midway Atoll in the NWHI (Randall et al., 1993). Despite these differences, the total number of species observed on quantitative transects in the NWHI (210) and was similar to the 215 species reported in a recent comprehensive quantitative study around the MHI (Friedlander et al., 2005). The lowest overall fish species richness in the NWHI occurs at the small basalt islands (Mokumanamana, Gardner, Nihoa). It is highest at French Frigate Shoals and Pearl and Hermes Atoll. Greater species richness at French Frigate Shoals may be related to higher coral richness and greater habitat diversity (Maragos et al., 2004) while large area, habitat diversity and the presence of subtropical and temperate species that occur at greater depths influence greater richness at Pearl and Hermes.

Reef fish trophic structure in the NWHI is strongly dominated by carnivores (Hobson, 1984; DeMartini and Friedlander, 2006). Fish biomass in the NWHI is nearly three times greater than in the MHI with most of the difference resulting from large apex predators (primarily sharks and jacks; Friedlander and DeMartini, 2002). Today, these top carnivores, analogous to lions and wolves on land, are seldom encountered by divers in the inhabited Hawaiian Islands. A number of species such as the endemic spectacled parrotfish (*Chlorurus perspicillatus*), the endemic Hawaiian hogfish (*Bodianus bilunulatus*), and bigeye emperor (*Monotaxis grandoculis*) are quite abundant and obtain large size in the NWHI. These species are heavily exploited for commercial, subsistence and recreational use in the MHI, and their reduced number and sizes in the MHI is likely the result of years of chronic overfishing (Friedlander and DeMartini, 2002).

Seabirds

Seabird colonies in the NWHI constitute one of the largest and most important assemblages of seabirds in the world, with approximately 14 million birds (5.5 million breeding annually) representing 22 species (Friedlander et al., 2005; USFWS, 2005). More than 95% of the world's Laysan albatross (*Phoebastria immutabilis*; Figure 1.8) and Black-footed albatross (*P. nigripes*) nest in the NWHI (USFWS, 2005). For several other species such as Bonin Petrel (*Pterodroma hypoleuca*), Christmas Shearwater (*Puffinus nativitatis*), Tristram's Storm-petrel (*Oceanoframa tristrami*) and Grey-backed Tern (*Sterna lunata*), the NWHI supports colonies of global significance. The last complete inventory of NWHI breeding populations was done between 1979 and 1984 (Fefer et al., 1984). Population trends since then have been derived from more intensive monitoring at three islands and are stable or increasing for most species at these locations but there is concern for a few, especially the albatross due to ingestion of plastics, loss of forage base and other large-scale issues (USFWS, 2005).

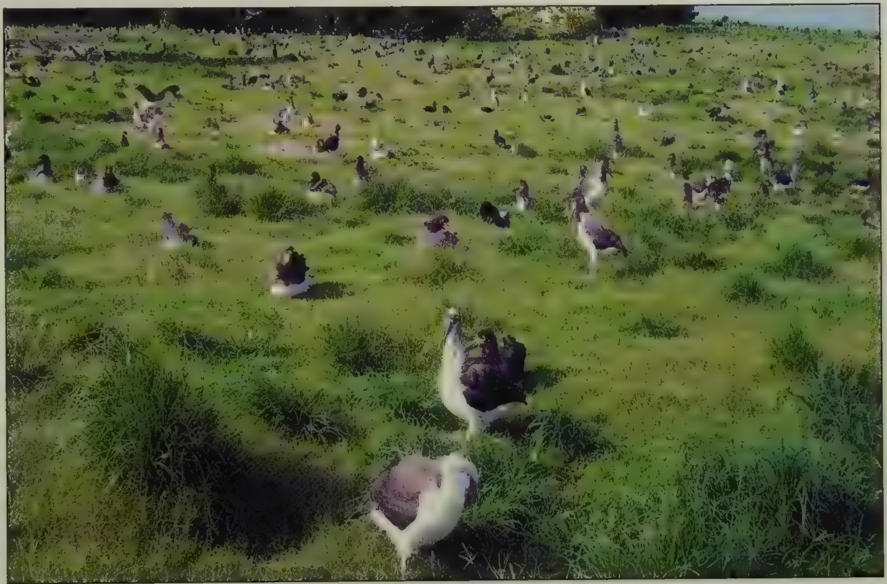


Figure 1.8. Laysan Albatrosses at Midway Atoll NWR. Photo: A. Friedlander.

Protected Species

Hawaiian Monk Seal

The Hawaiian monk seal (*Monachus schauinslandi*) is listed as Endangered under the Endangered Species Act (ESA) and Depleted under the Marine Mammal Protection Act. It is the only endangered pinniped occurring entirely within U.S. waters. Monk seals occur throughout the Hawaiian Archipelago, and although most are found in the NWHI, a small but increasing number pup in the MHI. They commonly occur on isolated beaches for resting, molting, birthing and nursing offspring, spending nearly two-thirds of their time in marine habitats (Antonelis et al., 2006). A recent monk seal recovery report estimates that there are only 1,200 Hawaiian monk seals still alive (Figure 1.9) and if the declining population trend continues there will be fewer than 1,000 within the next three or four years, a decrease of more than 60% since the 1950s. When compared historically, the monk seal beach count abundance index reached record lows in 2005.

Hawaiian Green Sea Turtle

The green sea turtle (*Chelonia mydas*) is the most abundant large marine herbivore globally (Bjorndal, 1997) and has a circumtropical distribution with distinct regional population structures (Figure 1.10; Bowen et al., 1992). Worldwide, the green turtle has been subject to a long history of human exploitation with some stocks now extinct and others in decline. Green sea turtles in U.S. waters have been protected under the federal ESA since 1978. The Hawaiian green turtle stock, or honu, comprises a single closed genetic stock that is endemic to the Hawaiian Archipelago (Bowen et al., 1992) with numerous distinct foraging grounds within the 2,200 km span of the Hawaiian Archipelago From the mid-1800s until about 1974, the Hawaiian stock was subject to human exploitation such as turtle harvesting at foraging grounds, harvesting of nesters and eggs, and nesting habitat destruction.

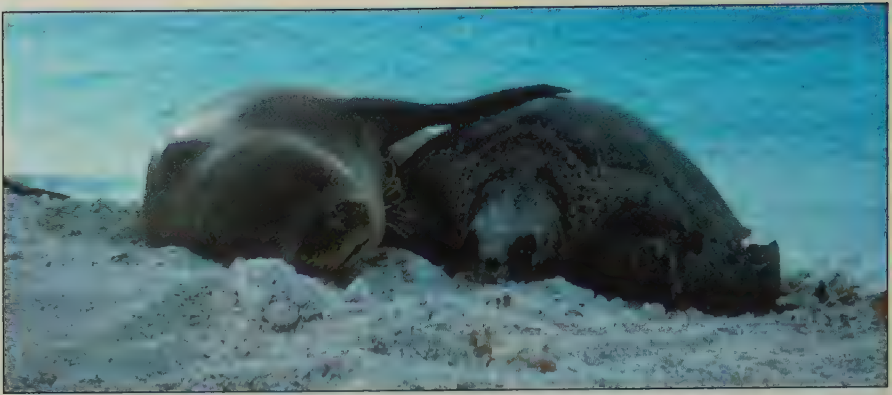


Figure 1.9. Hawaiian monk seal and endemic Hawaiian green sea turtle at NWHI. Photo: National Marine Fisheries Service.

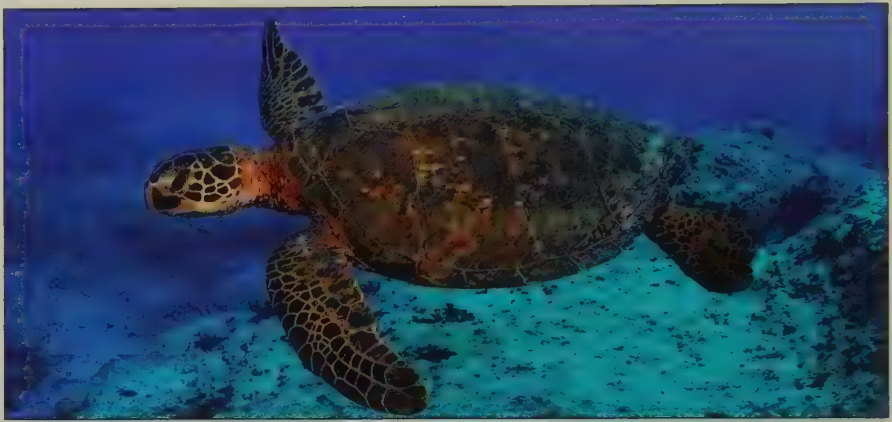


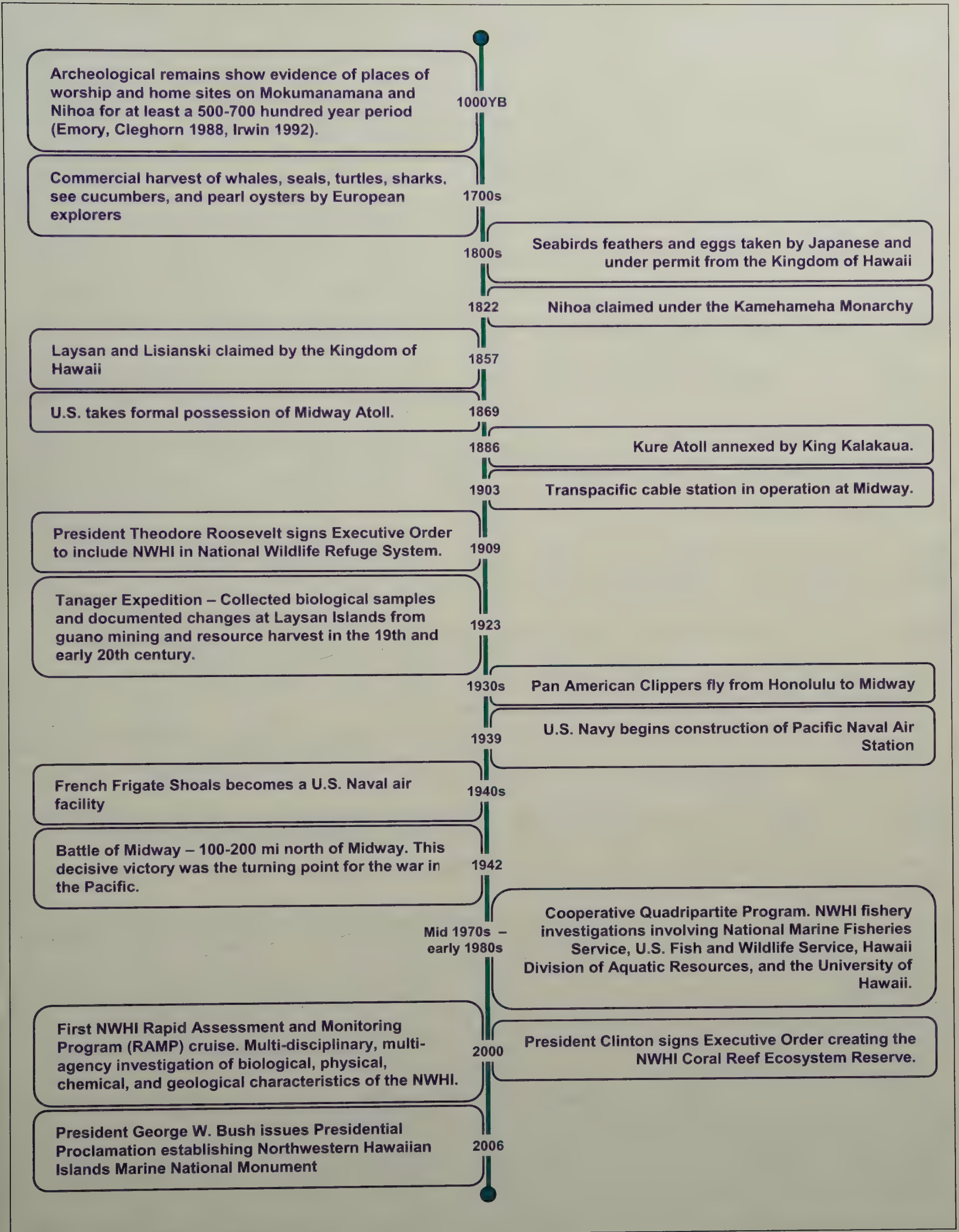
Figure 1.10. Endemic Hawaiian green sea turtle at Midway Atoll. Photo: J. Watt.

The primary rookery for the Hawaiian green sea turtle is located on French Frigate Shoals which accounts for more than 90% of all nesting within the Hawaiian Archipelago. The main rookery island at French Frigate Shoals is East Island where at least 50% of all French Frigate Shoals nesting occurs. Nesting females exhibit strong island fidelity, and the Hawaiian green sea turtle stock has been continuously monitored for several decades. Annual surveys of the number of female green turtles coming ashore to nest each night have been conducted at East Island since 1973 (Balazs, 1980).

The long-term trends based on a population model for the East Island nester abundance illustrates a dramatic increase in abundance over the past 30-years, and substantial fluctuations in the number of annual nesters has been observed (Balazs and Chaloupka, 2006). Such fluctuations are characteristic of green turtle nesting populations and reflect a variable proportion of females in the population that breed each year in response to ocean-climate variability. The Hawaiian green sea turtle stock is showing signs of recovering after more than 25 years of protecting their nesting and foraging habitats in the Hawaiian Archipelago (Chaloupka and Balazs, 2007).

HISTORY OF USE AND MANAGEMENT

The designation of the Monument is the most recent increase in protections and management of the NWHI. The NWHI has a long history of human use and increasing efforts for conservation management (Figure 1.11). Native Hawaiians traversed and seasonally used the NWHI for hundreds of years and continue today to maintain their strong cultural ties to the land and sea of the NWHI. Post-Western-contact, the NWHI continued to be explored and the harvest of natural resources including guano mining, egg harvesting, fishing and other natural resource extraction occurred. The U.S. Military maintained active military bases during much of the 1900s. In 1909 the first natural resource protection was put in place with the designation of the Hawaiian Islands Bird Reservation. Since that time, additional reserves and refuges have been established to protect this unique ecosystem. The most recent protections were implemented with the designation of the Papahanaumokuakea Marine National Monument June 15, 2006.



1000YB	Archeological remains show evidence of places of worship and home sites on Mokumanamana and Nihoa for at least a 500-700 hundred year period (Emory, Cleghorn 1988, Irwin 1992).
1700s	Commercial harvest of whales, seals, turtles, sharks, see cucumbers, and pearl oysters by European explorers
1800s	Seabirds feathers and eggs taken by Japanese and under permit from the Kingdom of Hawaii
1822	Nihoa claimed under the Kamehameha Monarchy
1857	Laysan and Lisianski claimed by the Kingdom of Hawaii
1869	U.S. takes formal possession of Midway Atoll.
1886	Kure Atoll annexed by King Kalakaua.
1903	Transpacific cable station in operation at Midway.
1909	President Theodore Roosevelt signs Executive Order to include NWHI in National Wildlife Refuge System.
1923	Tanager Expedition – Collected biological samples and documented changes at Laysan Islands from guano mining and resource harvest in the 19th and early 20th century.
1930s	Pan American Clippers fly from Honolulu to Midway
1939	U.S. Navy begins construction of Pacific Naval Air Station
1940s	French Frigate Shoals becomes a U.S. Naval air facility
1942	Battle of Midway – 100-200 mi north of Midway. This decisive victory was the turning point for the war in the Pacific.
Mid 1970s – early 1980s	Cooperative Quadripartite Program. NWHI fishery investigations involving National Marine Fisheries Service, U.S. Fish and Wildlife Service, Hawaii Division of Aquatic Resources, and the University of Hawaii.
2000	First NWHI Rapid Assessment and Monitoring Program (RAMP) cruise. Multi-disciplinary, multi-agency investigation of biological, physical, chemical, and geological characteristics of the NWHI.
2000	President Clinton signs Executive Order creating the NWHI Coral Reef Ecosystem Reserve.
2006	President George W. Bush issues Presidential Proclamation establishing Northwestern Hawaiian Islands Marine National Monument

Figure 1.11. Time line of the history of the NWHI use and management.

REFERENCES

Aeby, G.S. 2006. Baseline levels of coral disease in the Northwestern Hawaiian Islands. Atoll Research Bulletin 543:471-488.

Andrews, K.R., L. Karczmarski, W.W.L. Au, S.H. Rickards, C.A. Vanderlip, and R.J. Toonen. 2006. Patterns of genetic diversity of the Hawaiian spinner dolphin (*Stenella longirostris*). Atoll Research Bulletin 543: 65-73.

Antonelis, G.A., J.D. Baker, T.C. Johanos, R.C. Braun, and A.L. Harting. 2006. Hawaiian monk seal (*Monachus schauinslandi*): status and conservation issues. In: I.G. Macintyre (ed.). Northwestern Hawaiian Islands Third Scientific Symposium. November 2-4, 2004. Atoll Research Bulletin. No. 543. http://www.botany.hawaii.edu/faculty/duffy/arb/543/06.pdf

Baker, J.D. and T.J. Johanos. 2002. Effects of research handling on the endangered Hawaiian monk seal. Mar Mamm Sci 18: 500–512.

Balazs, G.H. 1980. Synopsis of biological data on the green turtle in the Hawaiian Islands. NOAA-TM-NMFS-SWFS-7.

Balazs, G.H. and M. Chaloupka. 2006. Recovery trend over 32 years at the Hawaiian green sea turtle rookery of French Frigate Shoals. Atoll Research Bulletin 543: 147-158.

Bernardi, G., S.J. Holbrook, R.J. Schmitt, N.L. Crane, and E. DeMartini. 2002. Species boundaries, populations, and colour morphs in the coral reef three-spot damselfish (*Dascyllus trimaculatus*) species-complex. Proc. Roy. Soc. London 269: 599-605.

Bird, C.E., B.S. Holland, B.W. Bowen, and R.J. Toonen. 2007. Contrasting population structure in three endemic Hawaiian limpets (*Cellana* spp.) with similar life histories. Molecular Ecology 16: 3173-3187.

Bjorndal, K. A.. 1997. Foraging ecology and nutrition of sea turtles. pp.199-232. In: P.L. Lutz and J.A. Musick (eds.). The biology of sea turtles. CRC Press, Boca Raton.

Boland, R., B. Zgliczynski, J. Asher, A. Hall, K. Hogrefe, and M. Timmers. 2006. Dynamics of debris densities and removal at the Northwestern Hawaiian Islands coral reefs. In: I.G. Macintyre (ed.). Northwestern Hawaiian Islands Third Scientific Symposium. November 2-4, 2004. Atoll Research Bulletin. No. 543.

Bowen, B.W., A.B. Meylan, J.P. Ross, C.J. Limpus, G.H. Balazs, and J.C. Avise. 1992. Global population structure and natural history of the green turtle (*Chelonia mydas*) in terms of matriarchal phylogeny. Evolution 46(4): 865-881.

Christensen, V. and C. J. Walters. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecol. Model. 172: 109–139.

Cowen, R.K., C.B. Paris, and A. Srinivasan. 2006. Scaling Connectivity in Marine Populations. Science 311: 522-527.

Cowen, R.K., G. Gawarkiewicz, J. Pineda, S.R. Thorrold, and F.E. Werner. 2007. Population connectivity in marine systems: an overview. Oceanography 20(3): 14-21.

Craig, M.T., J.A. Eble, D.R. Robertson, and B.W. Bowen. 2007. High genetic connectivity across the Indian and Pacific Oceans in the reef fish *Myripristis berndti* (Holocentridae). Marine Ecology Progress Series 334: 245-254.

Crowder L.B., S.J. Lyman, W.F. Figueira, and J. Priddy. 2000. Sourcesink population dynamics and the problem of siting marine reserves. Bull. Mar. Sci. 66: 799–820.

Currin, C.A., S.C. Wainright, K.W. Able, and M.P. Weinstein. 2003. Determination of food web support and trophic position of the mummichog, *Fundulus heteroclitus*, in New Jersey smooth cordgrass (*Spartina alterniflora*), common reed (*Phragmites australis*) and restored salt marshes. Estuaries 26: 495-510.

DeMartini, E.E. and A.M. Friedlander. 2004. Spatial pattern of endemism in shallow water reef fish populations of the Northwestern Hawaiian Island. Mar. Ecol. Prog. Ser. 271: 281-296.

DeMartini E.E., A.M. Friedlander and S.R. Holzwarth. 2005. Size at sex change in protogynous labroids, prey body size distributions, and apex predator densities at NW Hawaiian atolls. Marine Ecology Progress Series 297: 259-271.

DeMartini, E.E. and A.M. Friedlander. 2006. Predation, endemism, and related processes structuring shallow-water reef fish assemblages of the Northwestern Hawaiian Islands. Atoll Research Bulletin 543: 237-256.

Donohue, M.J., R. Boland, C. Sramek, and G. Antonelis. 2001. Derelict fishing gear in the Northwestern Hawaiian Islands: Diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. Marine Pollution Bulletin 42(12): 1301–1312.

Ehler, R. 2004. Socio-economic assessment of commercial bottomfishing in the Northwestern Hawaiian Islands. Report to NOAA, NOS, National Marine Sanctuary Program. pp. 46.

Fefer, S.I, C.S. Harrision, M.B. Naughton, and R.J. Shallengerger. 1984. Synopsis of results of recent seabird research conducted in the Northwestern Hawaiian Islands. In: R.W. Grigg and K.Y. Tanoue (eds.). Proceedings of the Second Symposium on Resource Investigations in the Northwestern Hawaiian Islands Vol 1.

Friedlander, A.M. and E.E. DeMartini. 2002. Contrasts in density, size and biomass of reef fishes between the Northwestern and Main Hawaiian Islands: the effects of fishing down apex predators. Mar. Ecol. Prog. Ser. 230: 253-264.

Godwin, S., K.S. Rodgers, and P.L. Jokiel. 2006. Reducing potential impact of invasive marine species in the northwestern hawaiian islands marine national monument. Report to: Northwest Hawaiian Islands Marine National Monument Administration.

Goodman-Lowe, G. 1998. Diet of Hawaiian monk seal (*Monachus schauinslandi*) from the Northwestern Hawaiian Islands during 1991-1994. Marine Biology 132: 535-546.

Grigg, R.W. 1981. Acropora in Hawaii. Part II. Zoogeography. Pac. Sci. 35: 15-24.

Grigg, R.W. 1982. Darwin Point: a threshold for atoll formation. Coral Reefs 1: 29-34.

Grigg, R.W. 1983. Community structure, succession and development of coral reefs in Hawaii. Mar Ecol Prog Ser 11: 1-14.

Grigg, R.W. and K.Y. Tanoue. 1984. Proceedings of the second symposium on resource investigations in the Northwestern Hawaiian Islands, Honolulu, Hawaii. UNIHI-SEAGRANT-MR-80-04.

Grigg, R.W. 1988. Paleoceanography of Coral Reefs in the Hawaiian-Emperor Chain. Science 240(4860): 1737-1743.

Grigg, R.W., J. Polovina, A.M. Friedlander, and S.O. Rohmann. 2008. Biology of coral reefs in the Northwestern Hawaiian Islands. In: B.M. Riegl and R.E. Dodge (eds.). Coral reefs of the USA. Coral reefs of the world 1. New York: Springer. Ch. 14: pp. 573-594.

Harting, A.L. 2002. Stochastic simulation model for the Hawaiian monk seal. PhD thesis, Montana State University, Bozeman, M.T. Hobson, E.S. 1980. The structure of reef fish communities in the Hawaiian Archipelago. pp. 57-70 in (R.W. Grigg and R.T. Pfund, eds.) Proc Symp Status Resource Invest NWH, April 24-25, 1980. U HI Honolulu Sea Grant Misc Rep UNIHI-SEAGRANT-MR-80-04.

Hobson, L.A. 1980. Primary productivity of the North Pacific Ocean: a review. Salmonid ecosystems of the North Pacific. Oregon State University Press, Corvallis. pp: 231-246

Hourigan, T.F. and E.S. Reese. 1987. Mid-ocean isolation and the evolution of Hawaiian reef fishes. Trends in Ecology and Evolution 2: 187-191.

Jokiel, P.L. 1987. Ecology, biogeography and evolution of corals in Hawaii. Trends in Ecology & Evolution 2(7): 179-182.

Juvik S.P. and J.O. Juvik. 1998. Atlas of Hawaii, 3rd edition. University of Hawaii Press. Honolulu.

Kawamoto, K. and D. Gonzales. 2005. Summary of bottomfish landings in the Hawaiian Island Archipelago, 1996-2004. Pacific Islands Fisheries Science Center Internal Report IR-05-023. 9 pp.

Kay, E.A. and S.R. Palumbi. 1987. Endemism and evolution in Hawaiian marine invertebrates. Trends Ecol. Evol. 2: 183–187.

Kelley, C. 2000. Characterizing deepwater habitats in Hawaii using multibeam sonar and submersible technologies. Abstract. pp: 166. 9th International Coral Reef Symposium, Bali, Indonesia. October, 2000.

Kelley, C. and W. Ikehara. 2006. The impacts of bottomfishing on Raita and West St. Rogatien Banks in the Northwestern Hawaiian Islands. Atoll Res. Bull. 543: 305-318.

Kelley, C., R. Moffitt, and J.R. Smith. 2006. Description of bottomfish essential fish habitat on four banks in the Northwestern Hawaiian Islands. Atoll Res. Bull. 543: 319-332.

Kobayashi, D.R. 2006. Colonization of the Hawaiian Archipelago via Johnston Atoll: a characterization of oceanographic transport corridors for pelagic larvae using computer simulation. Coral Reefs 25: 407-417.

Kubota, M. 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. J. Phys. Oceanogr. 24: 1059–1064.

Leis, J.M. 1987. Review of the early life history of tropical groupers (Serranidae) and snappers (Lutjanidae). pp. 189-237. In: J.J. Polovina and S. Ralston (eds.). Tropical Snappers and Groupers: Biology and Fisheries Management. Westview Press, Boulder and London.

Leis, J.M. 1993. The pelagic stage of reef fishes: the larval biology of coral reef fishes. pp. 183-230. In: P.F. Sale (ed.). The Ecology of Fishes on Coral Reefs. Academic Press, San Diego.

Leonard, C.L., R.R. Bidigare, M.P. Seki, and J.J. Polovina. 2001. Interannual mesoscale physical and biological variability in the North Pacific Central Gyre. Progress In Oceanography 49(1-4): 227-244.

Maragos, J.E. and P.L. Jokiel. 1986. Reef corals of Johnston Atoll: one of the world's most isolated reefs. Coral Reefs 4: 141-150.

Meyer, C.G., K.N. Holland, and Y.P. Papastamatiou. 2007b. Seasonal and diel movements of giant trevally (*Caranx ignobilis*) at remote Hawaiian atolls: implications for the design of Marine Protected Areas. Marine Ecology Progress Series 333: 13-25.

Meyer, C.G., Y.P. Papastamatiou, and K.N. Holland. 2007a. Seasonal, diel and tidal movements of green jobfish (*Aprion virescens*, Lutjanidae) at remote Hawaiian atolls: Implications for Marine Protected Area design. Marine Biology 151: 2133-2143.

Moseman, S.M., L.A. Levin, C. Currin, and C. Forder. 2004. Colonization, succession, and nutrition of macrobenthic assemblages in a restored wetland at Tijuana Estuary, California. Estuarine, Coastal and Shelf Science 60: 755-770.

Mundy, B.C. 2005. Checklist of the fishes of the Hawaiian archipelago. Bishop Museum Bulletin in Zoology 6. Bishop Museum Press, Honolulu, Hawaii.

Myers, R.A. and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. Nature 423.

Myers, R.A. and B. Worm. 2005. Extinction, survival or recovery of large predatory fishes. Phil. Trans. R. Soc. B. doi:10.1098/rstb.2004.1573.

NOAA (National Oceanic and Atmospheric Administration). 2003. Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands (Draft). 160 pp.

Oda, D.K. and J.D. Parrish. 1981. Ecology of commercial snappers and groupers introduced to Hawaiian Reefs. pp. 59-67. In: Proc. 4th Int. Coral Reef Symp.

Oda D.K. and J.D. Parrish. 1987. Trophic ecology of the introduced taape (*Lutjanus kasmira*) in Hawaii. Bulletin of Marine Science 41: 639.

Okamoto, H. and B. Kanenaka. 1984. Preliminary report on the nearshore fishery resource assessment of the Northwestern Hawaiian Islands, 1977-82. pp. 123-143. In: R.W. Grigg and K.Y. Tanoue (eds.). Proc 2nd Symp Resource Invest NWHI, Vol 1. Sea Grant Misc Rep UNIHI-SEAGRANT-MR-84-01J.

Papastamatiou, Y.P, B.M. Weatherbee, C.G. Lowe, and G.L. Lowe. 2006. Distribution and diet of four species of carcharhinidae shark in the Hawaiian Islands: evidence for resource portioning and competitive exclusion. Mar. Ecol. Prog. Ser. 320: 239-251.

Parke, M. 2007. Linking Hawaii fisherman reported commercial bottomfish catch data to potential bottomfish habitat and proposed restricted fishing areas using GIS and spatial analysis. NOAA Technical Memo. NMFS-PIFSC-11.

Parrish, F.A. and K. Abernathy. 2006. Movements of monk seals relative to ecological depth zones in the lower Northwestern Hawaiian Islands. Atoll Research Bulletin 543: 115-130.

Parrish, F.A. and R.C. Borland. 2004. Habitat and reef-fish assemblages of banks in Northwestern Hawaiian Islands. Marine Biology 144: 1065-1073.

Parrish, J., L. Taylor, M. DeCrosta, S. Feldkamp, S. Sanderson, and C. Sorden. 1980. Trophic studies of shallow-water fish communities in the Northwestern Hawaiian Islands. pp. 175-188. In: R.W. Grigg and R.T. Pfund (eds.). Proc Symp Status Resource Invest NWH, April 24-25, 1980. U HI Honolulu Sea Grant Misc Rep UNIHI-SEAGRANT-MR-80-04.

Polovina, J.J. 1984. Model of a coral reef ecosystem. The ECOPATH model and its application to French Frigate Shoals. Coral Reefs 3: 1-11.

Polovina, J.J., E. Howell, D.R. Kobayashi and M.P. Seki. 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Progress In Oceanography 49(1-4): 469-483.

Ragen, T.J. and D.M. Lavigne. 1999. The Hawaiian monk seal: Biology of an endangered species. pp. 224-245. In: J. Twiss and R. Reeves (eds.). Conservation and management of marine mammals. Smithsonian Institution Press, Washington, DC.

Ramon M., P. Nelson, E. DeMartini, W. Walsh, and G. Bernardi. 2008. Phylogeography, historical demography, and the role of post-settlement ecology in two Hawaiian damselfish species. Marine Biology 153: 1207-1217.

Randall, J.E. 1987. Introductions of marine fishes to the Hawaiian Islands. Bull Mar Sci 41:490-502.

Randall J.E. 1998. Zoogeography of shore fishes of the Indo-Pacific region. Zool Stud (Taiwan) 37: 227–268.

Randall J.E. 2007. Reef and shore fishes of the Hawaiian Islands. Sea Grant College Program, University of Hawaii, Honolulu. 546 pp.

Randall, J.E., J.L. Earle, R.L. Pyle, J.D. Parrish, and T. Hayes. 1993. Annotated checklist of the fishes of Midway Atoll, Northwestern Hawaiian islands. Pac Sci 47: 356-400.

Rivera, M., C. Kelley, and G. Roderick. 2004. Subtle population genetic structure in the Hawaiian Grouper, *Epinephelus quernus* as revealed by mitochondrial DNA analyses. Biological Journal of the Linnean Society 81: 449-468.

Rocha, L.A., M.T. Craig, and B.W. Bowen. 2007. Phylogeography and the conservation genetics of coral reef fishes. Coral Reefs Invited Review 26: 501-512.

Rooney, J.J., P. Wessel, R. Hoeke, J. Weiss, J. Baker, F. Parrish, C.H. Fletcher, J. Chonjnacki, M. Garcia, R. Brainard, and P. Vroom. 2008. Geology and geomorphology of coral reefs in the northwestern Hawaiian Islands. pp: 519-571. In: B.M Riegl and R.E. Dodge (eds.). Coral reefs of the world vol. I. coral reefs of the USA. Springer-Vergal Publishing.

Schultz, J.K., R.L. Pyle, E. DeMartini, and B.W. Bowen. 2007. Genetic connectivity among color morphs of the flame angelfish, *Centropyge loriculus*. Marine Biology 151: 167-175.

Sladek Nowles, J. and A.M. Friedlander. 2004. Research priorities and techniques. pp. 187-233. In: J. Sobel and C. Dahlgren. (eds.). Marine Reserves; their science, design and use. Island Press. Washington, DC.

Stewart, B.S., G.A. Antonelis, J.D. Baker, and P.K. Yochem. 2006. Foraging Biogeography of Hawaiian monk seals in the Northwestern Hawaiian Islands. Atoll Research Bulletin 543: 131-146.

Treml E.A., P.N. Halpin, D.L. Urban, and L.F. Pratson. 2008. Modeling population connectivity by ocean currents, a graph-theoretic approach for marine conservation. Landscape Ecology 23: 19-36.

U.S. Fish and Wildlife Service. 2005. Seabird Conservation Plan Pacific Region.

Valles H., S. Sponaugle and H.A. Oxenford. 2001. Larval supply to a marine reserve and adjacent fished area in the Soufriere Marine Management Area, St. Lucia, West Indies. J Fish Biol 59: 157–177.

Victor, B.C. 1993. Settlement strategies and biogeography of reef fishes. pp. 231-260. In: P.F. Sale (ed.). The Ecology of Fishes on Coral Reefs. Academic Press, San Diego.

Vroom, P.S. and K.N. Page. 2006. Relative abundance of macroalgae (RAM) on Northwestern Hawaiian Island reefs. Atoll Research Bulletin 543: 533-548.

Vroom, P.S., K.N. Page, J.C. Kenyon, and R.E. Brainard. 2006. Algae-Dominated Reefs. American Scientist 94: 429-437.

WPRFMC (Western Pacific Regional Fisheries Management Council). 2004. Bottomfish and seamount groundfish fisheries of the Western Pacific region: 2002 Annual Report. Western Pacific Regional Fisheries Management Council, Honolulu, Hawaii.

Yoklavich, M.M., H.G. Greene, G.M. Cailliet, D.E. Sullivan, R.N. Lea, and M.S. Love. 2000. Habitat associations of deep-water rockfishes in a submarine canyon: an example of a natural refuge. Fish. Bull. 98: 625–641.

Oceanographic and Physical Setting

Arthur Desch[1], Timothy Wynne[1], Russell Brainard[2], Alan Friedlander[3,4] and John Christensen[1]

INTRODUCTION

The Northwestern Hawaiian Islands (NWHI) are set in a dynamic oceanographic and meteorological regime in the northern/central subtropical region of the Pacific Ocean (Figure 2.1). The boundary between the nutrient-poor surface waters of North Pacific Subtropical Gyre and the nutrient-rich surface waters of the North Pacific Subpolar Gyre frequently influence the NWHI region (Kazmin and Rienecker, 1996; Leonard et al., 2001; Polovina et al., 2001). This front shifts seasonally (Polovina et al., 2001) and migrates on interannual and decadal time scales, bringing colder and nutrient rich waters that are likely important to the productivity and ecology of the region (Polovina and Haight, 1999; Nakamura and Kazmin, 2003; Polovina, 2005). Longer-term changes, particularly those related to climate, are of concern since the reef ecosystems of the NWHI may not have encountered such conditions for hundreds, thousands or even millions of years (Rooney et al., 2008).

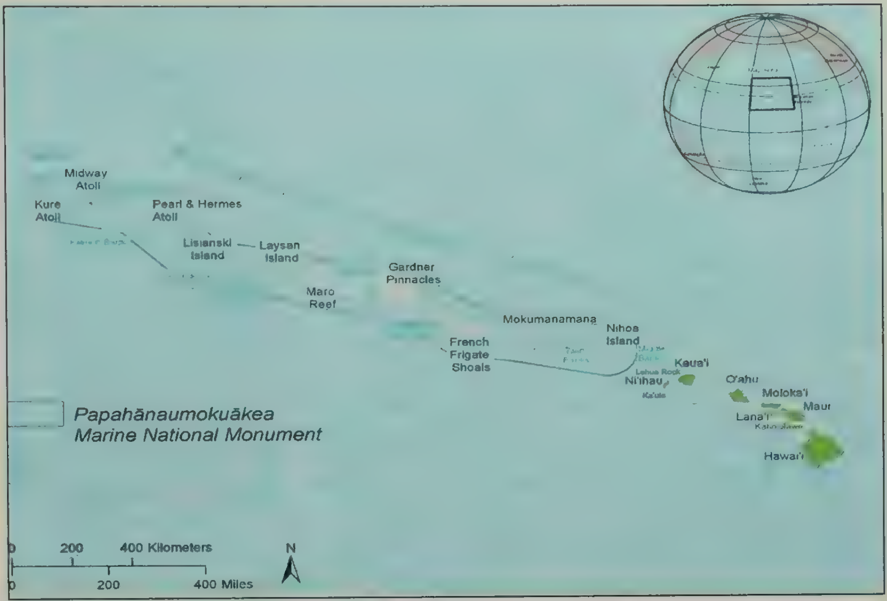


Figure 2.1. Hawaiian Archipelago Including the NWHI (Nihoa Island to Kure Atoll) and Main Hawaiian IslandsI (Hawaii to Kauai). Inset shows the Hawaiian Archipelago in the Pacific Ocean. Source: PMNM, 2008.

The health, functioning and biogeography of ecosystems of the NWHI are primarily controlled by the oceanographic processes and conditions, both physical and chemical, to which they are exposed. The Monument's diverse biological ecosystems, including fishes, corals and other invertebrates, algae, turtles, seabirds and marine mammals, is significantly influenced by ocean currents, waves, nutrients, temperature, and other measures of water quality and oceanographic conditions. The most important factors controlling the distribution and abundance of coral reefs in the NWHI are depth and shelter from large open ocean winter swell (Grigg. 1983).

This chapter provides a comprehensive analysis of ocean currents, waves, temperature, winds and productivity using satellite remote sensing data to offer a quantitative assessment of regional ocean climate. The objective is to capture spatial and temporal patterns in each of these parameters and to set context for the biogeographic assessment that follows. The Monument sits in a region of the Pacific Ocean that is dominated by large-scale circulation patterns that fluctuate over periods of years and decades. With that perspective, these data sets have been collected and analyzed over a spatial scale that includes much of the North Pacific Ocean. Large scale events and processes are the focus here. To illustrate this concept, Figure 2.2 provides a view of global sea surface temperature (SST), chlorophyll (ocean color), wind and sea surface height or SSH (proxy for currents). Each of these examples represents the average condition, worldwide, for the month of March. This view is provided as a reminder that while the NWHI cover a vast region, variability in oceanographic conditions as resolved by remote sensing platforms is most evident at basin-wide scales. That is, analysis of remote sensing data within the NWHI is not as variable as the Pacific basin as a whole. A short summary of regional cli-

---

1. NOAA/NOS/NCCOS/CCMA Coastal Oceanographic Assessment Status and Trends Branch
2. NOAA/NMFS/Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division
3. NOAA/NOS/NCCOS/CCMA Biogeography Branch
4. The Oceanic Institute

mate and oceanography is presented in advance of the quantitative analysis to provide points of reference for the results presented.

REGIONAL SUMMARY

Climate

The climate of the entire Hawaiian Archipelago features mild temperatures year-round, moderate humidity, persistent northeasterly trade winds and infrequent severe storms. Hawaii's climate is notable for its low day-to-day and month-to-month variability (Giambelluca and Schroeder, 1998). The climate is influenced by the marine tropical or marine Pacific air masses depending upon the season. During the summer, the Pacific High Pressure System dominates, with the ridge line extending across the Pacific north of Kure and Midway. This places the region under the influence of easterly winds, with marine tropical and trade winds prevailing. During the winter, especially from November through January, the Aleutian Low moves southward over the North Pacific, displacing the Pacific High (Grigg et al., 2008). The Kure-Midway region is then affected by either marine Pacific or marine tropical air, depending upon the intensity of the Aleutian Low or the Pacific High Pressure System (Amerson et al., 1974). The surrounding ocean has a dominant effect on the weather of the entire archipelago. Air temperature at the northern end of the archipelago varies between 11 and 33°C. Air temperature measurements made at six sites on Nihoa Island (23° N latitude) from March 2006 to March 2007 ranged between 16 and 34°C. Annual rainfall over the last 26 years has been 73.28 cm on average, ranging between 40.61 and 104.24 cm/year (PMNM, 2008).

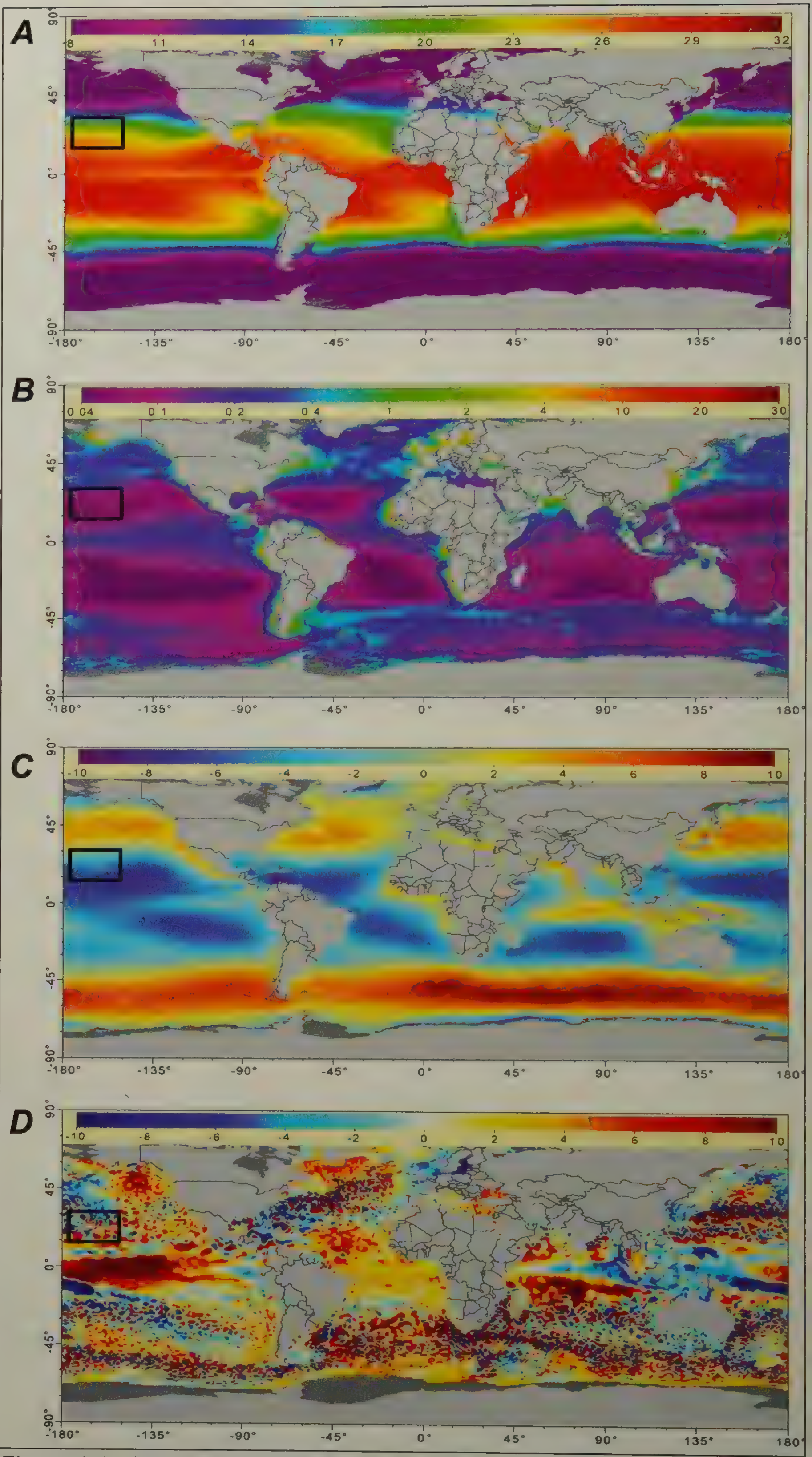


Figure 2.2. (A) Global climatological SST (ºC), (B) chlorophyll mg/m³, (C) wind m/sec (D) and sea surface height anomaly cm estimates for the month of March. The NWHI study area is shown as a black box.

El Niño – Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)

ENSO is an interannual global climate phenomenon that results from the large-scale coupling of atmospheric and oceanic processes, which creates significant temperature fluctuations in the tropical surface waters of the Pacific and other oceans. The two distinct ENSO signatures in the Pacific Ocean are known as El Niño and La Niña. During El Niño events, the Aleutian Low pressure system tends to be more intense and extend further to the south (closer to the NWHI), thereby producing stronger winds, larger waves and cooler water temperatures in the NWHI (Bromirski et al., 2005). During La Niña, SSTs in the eastern tropical Pacific are below average, and temperatures in the western tropical Pacific are above average (Figure 2.3). Leonard et al. (2001) and Rooney et al. (2008) have suggested that positive ENSO signatures (warming) correspond with southern extensions of the North Pacific subtropical front. A strong band of cool water (blue in false color range) appears along the Equator, particularly strong near South America. Warm conditions (orange in false color range) appear north and south of this strong blue band (Figure 2.3). The NWHI be seen straddling both warm and cold portions of the basin-wide temperature anomaly, highlighting complex regional thermal structure. Because biological communities are significantly influenced by spatially and temporally-varying ocean currents, temperature and nutrients (Polovina et al., 1995; Seki et al., 2002; Polovina et al., 2004), regional biogeography is equally complex and dynamic.

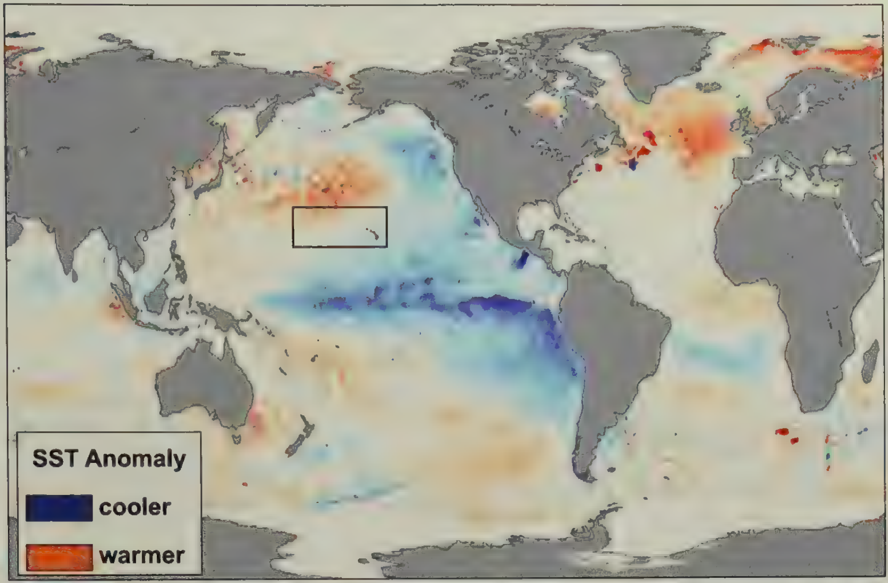


Figure 2.3. Diagram SST anomalies in November 2007 showing La Niña conditions. Blue tones indicate cooler than average surface temperatures, while orange tones indicate warmer than average. The Hawaiian Islands, including the NWHI are in the black box.

The PDO is a long-lived El Niño-like pattern of Pacific climate variability. While the two climate oscillations have similar spatial footprints, they have very different behavior in time. Two main characteristics distinguish PDO from ENSO are: 1) 20th century PDO events persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months; and 2) the climatic effects of PDO are most visible in the North Pacific, while secondary signatures exist in the tropics. The opposite is generally true for ENSO. Several independent studies provide evidence that two full PDO cycles have occurred over the past century, where cool regimes prevailed from 1890-1924 and again from 1947-1976, and warm regimes dominated from 1925-1946 and from 1977 through the mid-1990s. Additional research suggests that 20th century PDO fluctuations were most energetic in two general periodicities, one from 15-to-25 years, and the other from 50-to-70 years (http://jisao.washington.edu/pdo/).

Ocean Temperature

SST is an important physical factor influencing coral reefs and other marine ecosystems of the Monument. Maximum monthly climatological mean SST measured over the last 20 years at Kure is 27 °C in August and September (NOAA Pathfinder SST time series; Hoeke et al., 2006), with monthly minimums in February at 19 °C. The large seasonal temperature fluctuations at the northern end of the archipelago result in the coldest – and sometimes the warmest – SSTs in the entire Hawaiian chain (Brainard et al., 2004). At the southern end of the Monument, the annual variation in SST is much less, with French Frigate Shoals only varying between 23.3 and 27.5° C.

Winter temperatures tend to be 3-7°C cooler at the northerly atolls than at the southerly islands and banks as the subtropical front migrates southward. These cooler winter temperatures are thought to reduce coral growth rates (Grigg 1983, Grigg et al. 2008). In addition to the strong annual cycle, SST observations show significant interannual and decadal variability (Figure 2.4). The highest summer maximum SSTs at the northern atolls occurred during the summers of 1987, 1991 and 2002, possibly suggesting a teleconnection with ENSO events. Winter minimum temperatures at the northern atolls appear to oscillate over a longer time period, as indicated by a significant warming of winter SSTs beginning in 1999 and lasting for several years (Brainard et al., 2004). During the period between July and September 2002, ocean temperatures along the Hawaiian Archipelago were warmer than average.

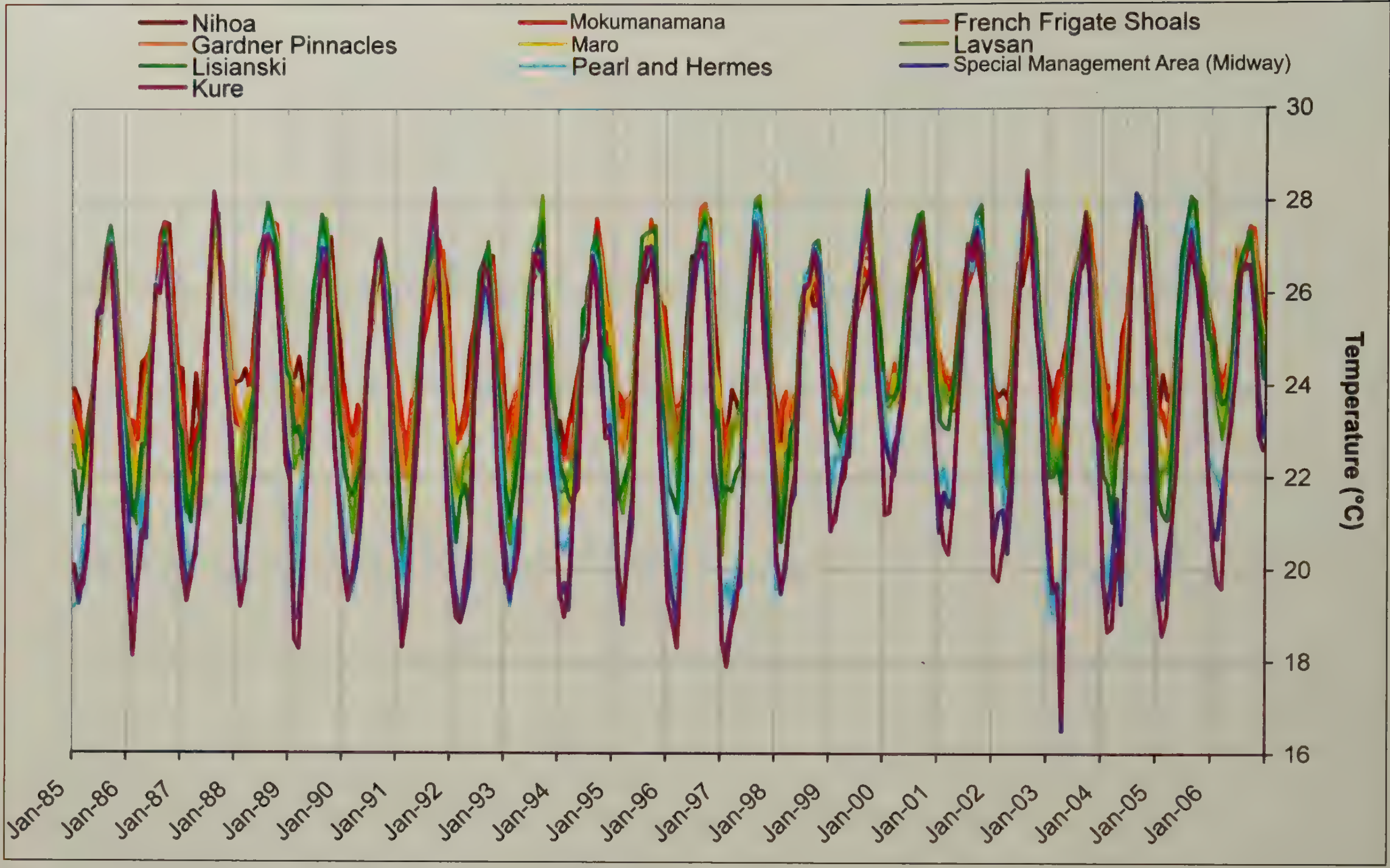


Figure 2.4. Pathfinder SST (°C) time-series for islands, atolls and shoals throughout the Monument (1985-2006).

While coral bleaching can be caused by a wide range of environmental variables acting alone or in combination (Jokiel and Brown, 2004), the predominant cause of increasing incidences of coral bleaching globally is believed to be persistent warmer than average water temperatures (Jokiel and Coles, 1990; Kenyon et al., 2006a,b), and indeed a significant bleaching event was documented during the summer of 2002 (Friedlander et al., 2005; Hoeke et al., 2006, Kenyon et al., 2006a,b).

Ocean Currents

Ocean currents transport and distribute larvae among and between different atolls, islands and submerged banks of the NWHI, and also provide the mechanism by which species are distributed to and from the main eight Hawaiian Islands, as well as other regions (Polovina et al., 1995). The relatively low species diversity and high endemism of the NWHI are the result of the relative oceanographic isolation of the Hawaiian Archipelago (Grigg et al., 2008; Demartini and Friedlander, 2004; Friedlander et al., 2008).

Ocean currents are measured and monitored in the NWHI in many different ways. Since 1990, ocean current profiles along the Hawaiian Archipelago have been measured using Acoustic Doppler Current Profilers (ADCP) aboard the NOAA ships *Townsend Cromwell* (1990 to 2002) and *Oscar Elton Sette* (2003 to present) during routine transects along the archipelago to support a number of scientific cruises for NOAA's Pacific Islands Fisheries Science Center (PIFSC).

Based on 10 years of ADCP data (1990-2000), Firing et al. (2004a) demonstrated that upper ocean currents in the NWHI are highly variable in both speed and direction. Averaged over time, the resultant mean flow of the surface waters tend to flow predominantly from east to west in response to the prevailing northeast trade winds. The lack of coral reef ecosystems and low biodiversity to the east, or upstream, of the Hawaiian Archipelago explains the low species richness and high endemism (PMNM, 2008). Surface Velocity Program current drifters and autonomous profiling explorer drifters have also been deployed in the NWHI by PIFSC annually since 2001. These drifters provide indications of the Lagrangian (or water-following) flow, thereby representing potential larval pathways (Firing et al., 2004a).

Ocean Waves

Common throughout the region and perhaps more significant as a natural process affecting the geology and ecology of the Monument, are the extra-tropical storms and significant wave events that regularly move across the North Pacific in the boreal winter (Friedlander et al., 2008, Grigg et al., 2008). Among each of the islands, atolls and submerged banks of the NWHI, the distributions of species of corals and algae, and their associated fish and invertebrate assemblages are often determined not only by the ocean currents, but also by the exposure to ocean waves. Many species of corals and algae can only survive in sheltered or quiescent habitats. Other species; however, can survive or even thrive in the high wave-energy habitats on the northwestern facing reefs that are exposed to tremendous waves caused by winter storms across the North Pacific.

These large wave events, greater than 10 m, influence the growth forms and distribution of coral reef organisms (Dollar, 1982; Dollar and Grigg, 2004; Grigg et al., 2008) and affect the reproductive performance of winter-breeding seabirds nesting on low islets in the Monument. Most large wave events, 5 to 10 m, approach the NWHI from the west, northwest, north and northeast, with the highest energy generally occurring from the northwest sector. The southern sides of most of the islands and atolls of the NWHI are exposed to fewer and weaker wave events. Annually, mean wave energy and wave power (energy transferred across a given area per unit time) are highest (approximately 1.3 W/m) between November and March and lowest (approximately 0.3 W/m) between May and September (Figure 2.5). Extreme wave events, 10 m or higher, affect shallow water coral reef communities with at least an order of magnitude more energy than the typical winter waves (Grigg et al., 2008).

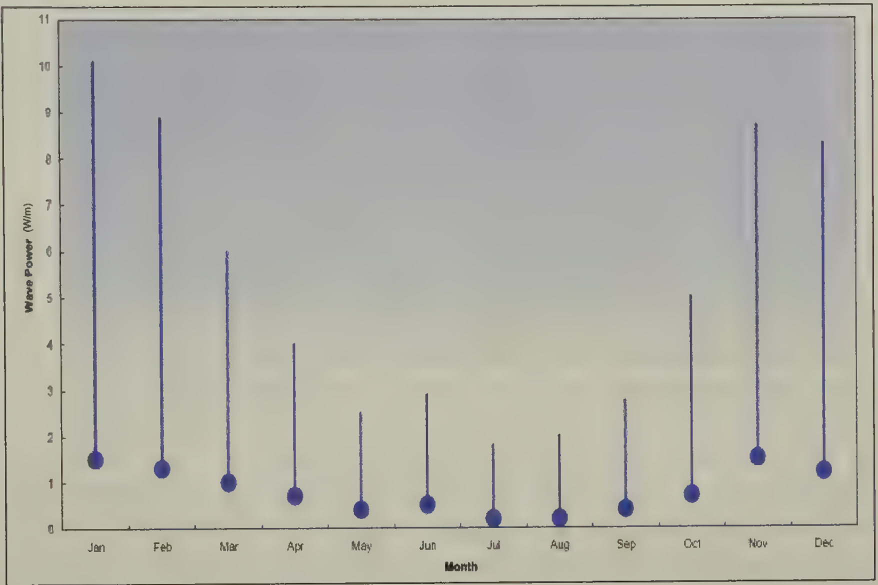


Figure 2.5. Diagram of Climatological values of wave power (W/m) derived from NOAA buoy # 51001 located near Nihoa Island from 1981 to 2003. Blue circles represent monthly means; blue lines represent wave power maxima. Source: NOAA NDBC.

Significant wave events vary over interannual and decadal time scales. This temporal variability of wave power allows expansions and retractions of the spatial and vertical ranges of the same species during relatively quiescent and turbulent years, respectively (Rooney et al., 2008). Over the past 20 years, wave measurements at NOAA buoy 51001 (near Nihoa Island in the NWHI) show a pattern of numerous extreme wave events during the periods 1985-1989 and 1998-2002 and low numbers of extreme wave events in the early 1980s and the period 1990-1996. This apparent decadal variability of wave power is possibly related to the PDO (Mantua et al., 1997). Studies have shown decadal oscillations of various components of NWHI ecosystems (lobsters, monk seals, seabirds, etc.) relate to larger scale climate shifts across the North Pacific (Polovina et al., 1995).

Primary Productivity / Ocean Color

Productivity in the NWHI is influenced by local and regional factors, and upwelling may occur in response to localized wind and bathymetric features (Friedlander et al., 2005). The Monument is located at the northern edge of the oligotrophic tropical Pacific, in the North Pacific central gyre ecosystem (Figure 2.6). Regional factors are largely influenced by the position of the subtropical front and associated high chlorophyll content of waters north of the front (PMNM, 2008). High chlorophyll waters intersect the northern portions of the NWHI during southward winter migrations of the subtropical front. The influx of nutrients to the NWHI from these migrations is considered a significant factor influencing different trophic levels in the NWHI (Polovina et al., 1995). It is near the 18°C isotherm, a major ecological transition zone in the northern Pacific. This boundary, also known as the "chlorophyll front", varies in position both seasonally and annually, occasionally transgressing the

Monument boundary and surrounding the northern atolls of Kure and Midway (PMNM, 2008).

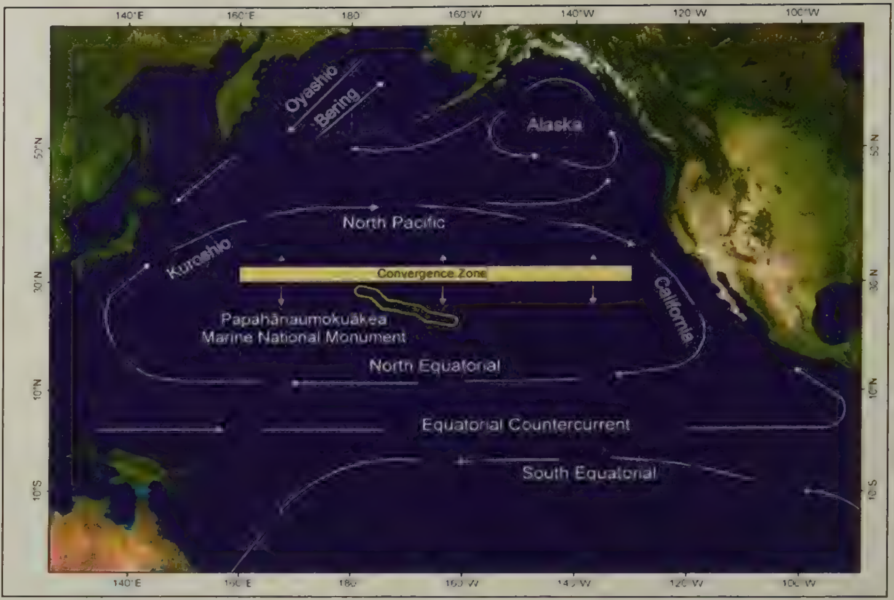


Figure 2.6. Diagram of Central Pacific Gyre. The North Pacific, California, North Equatorial, and Kuroshio currents along with atmospheric winds generate the North Pacific Subtropical Gyre. The subtropical Convergence Zone, an area where marine debris is known to accumulate, shifts seasonally between 23ºN and 37ºN latitude.

Movement of this front influences overall ocean productivity, and resultant recruitment of certain faunal elements such as Hawaiian monk seals and Laysan and Black-footed Albatrosses (Polovina et al., 1994). The northernmost atolls also are occasionally affected by an episodic eastward extension of the Western Pacific warm pool, which can lead to higher summer ocean temperatures at Kure than are found in the more "tropical" waters of the MHI further south (Hoeke et al., 2006). This interplay of oceanography and climate is still not completely understood, but is a dynamic not seen in most other tropical atoll ecosystems. As a result, it provides a useful natural laboratory for understanding phenomena such as periodic coral bleaching and the effects of El Niño and La Niña ocean circulation patterns (see ocean temperature).

Satellite observations of ocean color from the National Aeronautics and Space Administration's (NASA) Sea-viewing Wide Field-of-view Sensor (SeaWiFS) reveal a significant chlorophyll front associated with the subtropical front, with high chlorophyll north of the front and low oligotrophic waters south of the front. These observations reveal significant seasonal and interannual migrations of the front northward during the summer months and southward during the winter months (Seki et al., 2002). The southward migration of the subtropical front generally brings these high chlorophyll waters to intersect the northern portions of the NWHI. During some years, these winter migrations of the subtropical front extend southward to include the northern end of the NWHI. Additional evidence suggests decadal scale movements in the southward extent of the subtropical front. During periods when high chlorophyll waters intersect the NWHI, overall productivity of the affected reef ecosystems is expected to be elevated. Changes across many trophic levels of the NWHI ecosystem are believed to be associated with these migrations (Polovina et al., 1995).

OCEAN REMOTE SENSING ANALYSIS: DATA AND METHODS

This oceanographic assessment is based largely on data acquired from satellite and *in situ* sensors to characterize conditions for each of the management areas within the Monument, as well as the larger ecological region. For this report, the study area is defined as: north bounding coordinate – 45ºN; south bound – 15ºN; east bound – 145ºW; and west bound – 175ºE. Spatial patterns in the temperature, temperature fronts and chlorophyll were identified, as well as the variability in those patterns. Time series information was also extracted from the datasets to investigate trends at a variety of time-scales.

The Monument includes 10 special management zones and eco-regions. These management regions are centered on relatively untouched islands, reefs and atolls that are home to thousands of species, some that are found nowhere else on earth. The oldest (approximately 28 million years old) and most northern are Kure Atoll, Midway Island and Pearl and Hermes Atoll. These three ecosystems are subject to similar oceanographic influences and will be analyzed together as the northern grouping. The adjacent, and next most southeasterly grouping – Lisianski Island, Laysan Island, Maro Reef and Gardner Pinnacles – lie along the same latitudinal zone and exhibit similar temperature and chlorophyll climatological profiles, as well as being subjected to similar current regimes. These will be analyzed together as the central group. The most southern and youngest (7-12 million years old) of the atolls are French Frigate Shoals, Mokumanamana Island, and Nihoa Island (Figure 2.7). These three experience milder SSTs, smaller temperature ranges through the year and are less impacted by winter storm waves.

The study area encompasses a region much larger than the Monument boundaries so as to allow ecosystem-scale information to be included in management decisions. Much of the oceanographic variety in the region of the Monument happens well away from the atolls themselves. The northern group of atolls is the only which experiences extreme events and changes on a fairly regular basis. Even though the Monument itself is relatively calm compared to the ocean environment around it, the more extreme events of the central pacific influence the migration of fauna in and around the Monument atolls, and thus must be considered.

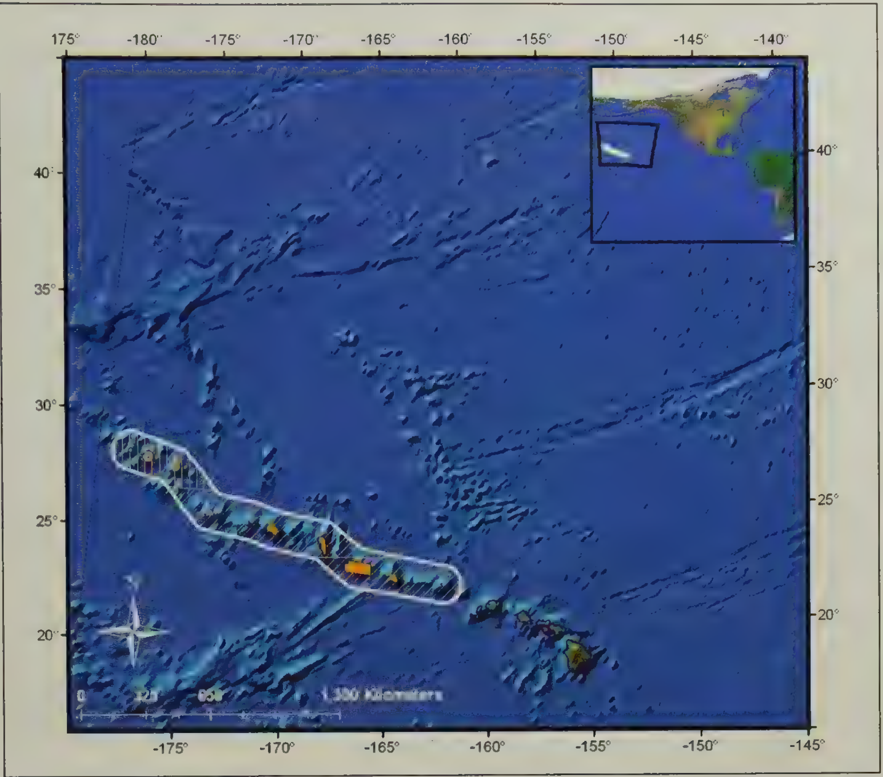


Figure 2.7. Locator map of the study area. Cross-hatched regions represent the northern, central, and southern analysis areas.

Data Assembly and Processing

The majority of remote sensing data products were obtained as monthly composites (mean), and subsequently processed into seasonal and interannual monthly means and medians. Seasonal means were calculated using the following constraints: winter (January, February, March); spring (April, May, June); summer (July, August, September); and fall (October, November, December). Production of a consistent time series of imagery in this manner allowed extraction of data from each source within regions of interest, and for regional averages within the bounds of the entire Monument. These time series were extracted for 10 locations in the study region (Figure 2.7, orange polygons), as well as the three regional groupings and the Monument as a whole for preliminary analyses of episodic, seasonal and interannual patterns. Interannual monthly means were then derived from the extracted time series. These data composites over the entire Monument, or for specific locations, were created to summarize trends and to highlight episodic and seasonal events useful for interpreting biogeographic patterns discussed later in this report. Time series images consist of all monthly mean or median data for each month over time. For example, the month of January has an image of mean chlorophyll for each of the years 1998 to 2007. These 10 monthly images are then averaged to obtain an interannual mean of chlorophyll. Monthly and seasonal anomaly images were produced to illustrate the differences between the long-term interannual mean and the monthly image.

Chlorophyll

Chlorophyll products were derived from data obtained from SeaWiFS. SeaWiFS data for research and educational applications have been available through the NASA since its launch in September of 1997 through December 2007. The sensor provides reliable daily observations for the United States at a nominal spatial resolution of 1.1 km for spectral bands encompassing the visible and near-infrared spectrum. The 4 km Global Area Coverage (GAC) product was used because data quality and density of the 1.1 km data was insufficient in the NWHI region (Figure 2.8).

The entire SeaWiFS GAC dataset was processed with SeaDAS version 5, applying the improved algorithms and obtaining georeferenced chlorophyll-a data at 4-km spatial resolution for the central Pacific region. Products were created for the central Pacific region specifically to include the boundaries of the Monument and also encompass the surrounding environment to allow management and scientific inquiry to include the greater ecosystem contextual processes. Estimations of chlorophyll-a in units of µg/L were derived using the standard OC4v4 equation that NASA used for global products from SeaWiFS. NOAA's Center for Coastal Monitoring and Assessment (CCMA) has developed algorithms, implemented by NASA for standard processing, to improve the generation of ocean color data and estimation of chlorophyll from SeaWiFS (Stumpf et al., 2003).

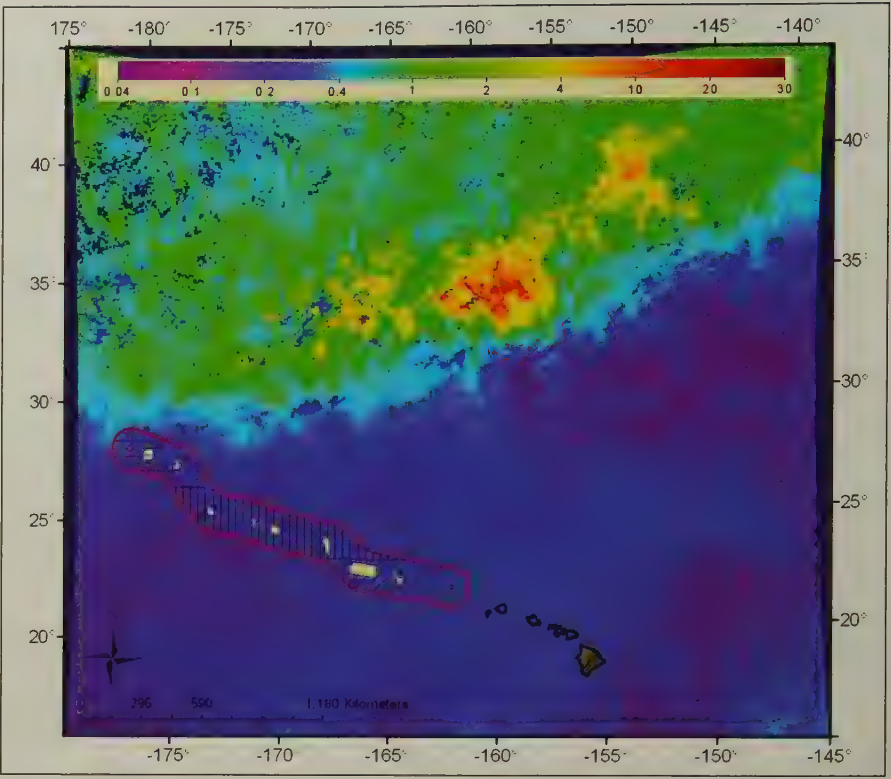


Figure 2.8. Example Global Area Coverage (GAC) chlorophyll distribution throughout the study region (April 2004). Warm tones represent high chlorophyll, while cool tones represent lower estimated chlorophyll concentrations (Units are µg/L).

Chlorophyll-a is the dominant pigment in marine photosynthetic organisms, and is referred to simply as chlorophyll within this report. Time series image sets of chlorophyll were created for the specified regions in Geotiff format. These time series images are useful for determining trends in algal bloom activity and ocean productivity. Final products were projected using the Albers Conical Equal Area (ACEA) projection with the World Geodetic System 1984 (WGS-84) datum. The imagery time series generated from the SeaWiFS data are monthly medians. Seasonal means were created from the appropriate monthly median files resulting in a seasonal image (seasons previously defined), and interannual monthly and seasonal files were generated using all monthly images for a particular month (or season) in the time series as input.

Sea Surface Temperature and Frontal Boundaries

SST data were developed from the NASA Pathfinder Version 5.0 dataset. This dataset derives a climatological grade SST product from Advanced Very High Resolution Radiometer (AVHRR) imagery, which was generated from several NOAA Polar-orbiting Environmental Satellites between 1985 and the present. The Pathfinder dataset was calibrated for inter-comparison of the temperature data across the entire period, facilitating climate and other studies (NASA, 2004; NASA, 2005). Ocean fronts data, regions that delineate the boundary between different water masses, were obtained from the Geostationary Operational Environmental Satellite (GOES).

Fronts were generated from GOES 2000-2006 hourly images (averaged to months) sampled to 4 km (Figure 2.9). Fronts were identified in each image using an algorithm developed by Canny (1986). Front occurrences were tallied at each pixel location for a month, season or year as needed. Climatological means were also created. Data products were mapped and subset to the study area. Geotiffs were created using the ACEA projection with the WGS-84 datum (Figure 2.9).

Spatial resolution of the Pathfinder data varies slightly with latitude, with a horizontal resolution of approximately 4 km at 35 degrees of latitude. Pathfinder is distributed along a 0.04 degree grid in Cartesian coordinates. The original global 4 km data were subset to the study area bounds. Geotiffs were created of the monthly mean time series (1985-2006) using the ACEA projection with the WGS-84 datum. SST image datasets were created from monthly means for the region; units are degrees Celsius (°C).

Ocean Currents

The calculation of SSH is based on a reference ellipsoid. This reference ellipsoid is a raw approximation of Earth's surface, a sphere flattened at the poles. This position is determined relative to an arbitrary reference surface, an ellipsoid. The satellite altitude above the reference ellipsoid (distance S) is available to within 3 cm. The SSH, is the range at a given instance from the sea surface to a reference ellipsoid. Since the sea depth is not known accurately everywhere, this reference provides accurate, homogeneous measurements. The sea level is simply the difference between the satellite height and the altimetric range.

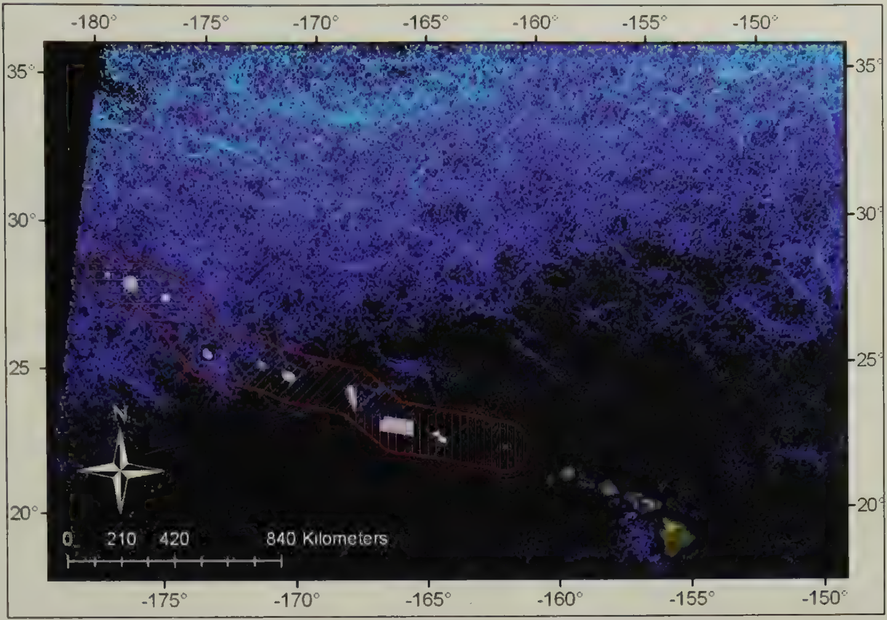


Figure 2.9. Example average sea surface frontal boundaries for the region (April, 2005). Dense clustering of boundaries, and lighter tones indicate elevated frontal boundary detection. Note higher frontal activity in the northern and western reaches of the Monument.

Merged sea surface height anomaly (SSHA) data from altimetry were obtained from Archiving, Validation and Interpretation of Satellite Data in Oceanography (AVISO) delayed time products of SSH generated from merged Topex/Poseidon (T/P), Jason-1/2, ERS-1/2 and ENVISAT missions. Merged SSHA data from altimetry were obtained from AVISO delayed time products of SSH generated from merged Topex/Poseidon (T/P), Jason-1/2, ERS-1/2 and ENVISAT missions. Weekly (seven-day) and monthly averaged data were used. Monthly estimates of vertical SSH from mean sea level were obtained following a simple bin averaging technique. A calendar of monthly averaged SSHA data to dissect climatological patterns of space-time variability for the region of interest is shown.

Post processing involved conversion from Network Common Data Format (NetCDF) format to raw binary image format, binning of weekly SSHA data, georeferencing and tiff generation of by-products. The binning procedure followed a simple arithmetic averaging technique to compute a monthly estimate of vertical SSH from mean sea level. Map projection is a 1/4° geographic (lat/long) projection grid, where number of values for X (found in file) = 1,080 and number of values for Y (found in file) = 720. Final georeferenced products were converted to 32 bit Geotiffs (v6). 8 bit Geotiffs were also created for reference. The time period for SSHA data analyzed here range from October 1992 to present.

Winds

NOAA's National Centers for Environmental Prediction (NCEP) generates global wind data termed "reanalysis winds" which are processed using a state of the art analysis system, and are used primarily for long-term climate studies. The data were produced at a 2.5 degree spatial resolution. NCEP uses all available atmospheric data to model winds every six hours, and is available from January 1, 1948 through the present. Reanalysis winds are distributed in NetCDF, and have a time component, latitude, longitude, zonal component (u) and a meridional component (v).

From the u and v wind components, direction (in degrees) and magnitude (in speed; m/s) can easily be derived. The data are available for 17 different pressure levels. To estimate the winds closest to the atmosphere-ocean interface we chose the highest pressure level (1,000 millibars). Using the six hour observations, NCEP calculates daily, monthly, and annual average and standard deviation reanalysis wind products. NOAA's CCMA has created direction and speed images created as 32-bit Geotiffs in geophysical units primarily for qualitative assessment purposes and an 8-bit scaled Geotiff version primarily designed for quantitative assessments. Monthly, seasonal and annual means for the study region have been created in this fashion.

The monthly data from NASA's Quick Scatterometer (QuikSCAT) was obtained and processed form from the French Institute for Exploring the Sea (IFREMER). Scatterometers, such as QuikSCAT, measure the roughness of the surface of the ocean, which in turn may be used as a proxy to estimate wind speed and direction. Scatterometer data are not available near or adjacent to land. The QuikSCAT NetCDF data files were generated from monthly data composites that covered the period ranging from August 1999 though February 2007. Seasonal and yearly climatological files were generated through the combination of monthly data composites that covered the period January 2000 though December 2006. The data were spatially subset to the study area at a spatial resolution of 0.5 degrees per pixel. Each file contained the following parameters: wind stress curl (Pa/m), wind speed divergence (m/s), wind speed (m/s), zonal wind speed (m/s), meridional wind speed (m/s), wind stress (Pa), meridional wind stress (Pa) and zonal wind stress (Pa; IFREMER, 2002). The resulting data files for each parameter were converted to 8-bit and 32-bit Geotiff format, in the same manner as the reanalysis wind products.

OCEAN REMOTE SENSING ANALYSIS: RESULTS

Sea Surface Temperature

Latitude is a primary driver in oceanographic conditions of the Monument and SST is highly correlated with latitude. This is evident in the stratification of SST within the Monument moving from north to south. SST analysis suggests that the 10 management regions can be segregated into three latitudinal subgroups. Mean SST highs in August and September are similar for all of the regions, around 27°C, but lows in February and March are varied and highlight the latitudinal differences (Figure 2.10).

The northern atoll group (Kure, Pearl and Hermes and Midway) has a wide range of temperatures throughout the year, typically from around 20°C in February to 27°C during the summer; however, temperatures have reached as low as 16°C and as high as 29°C. This range is one of the widest temperature ranges for any coral reef system on the planet (Friedlander et al., 2005). In addition, the northern islands are unexpectedly warmer in the summer than the most southern atolls of Nihoa, Mokumanamana and French Frigate Shoals. This north-south temperature stratification results in a latitudinal partitioning of flora and fauna causing endemic species and species composition changes within the Monument (Polovina et al., 1995; Friedlander et al., 2005).

Average monthly SST images clearly show the seasonal variation and north-south temperature gradient in the NWHI (Figure 2.11). The southern region experiences warmer temperatures compared to those in the north, but less variability throughout the year, while the northern atolls have much more variability within and between years (Figures 2.4 and 2.11). The southernmost island grouping (French Frigate Shoal, Mokumanamana Island, and Nihoa island) experience an environment with a restricted range in temperature when compared to islands to the north and west; approximately 23°C in the winter to 27°C in the summer. Summer SSTs for this group are generally lower than or the same as the northern atoll group. This is possibly due to weaker winds in the north, caused by proximity to the North Pacific high pressure ridge, resulting in less mixing with subsurface waters (Hoeke et al., 2006).

Pattern and periodicity in SSTs within the Monument are remarkably stable from 1985-2006 (Figure 2.12). Anomalies are rarely more than a degree from the long-term mean and typically occur during the winter months (Figure 2.12). Wintertime negative temperature anomalies occurred in June 1987, May 1992, December 1996, February 1997 and June 1997, while positive anomalies occurred during the early spring in 1999, 2000 and 2001 (Figure 2.12). These observed anomalous variations in SST are likely associated with the interactions and state of the PDO and ENSO and trend strongly towards the phase of the PDO, either warm or cold. There is less observed variability during the summer months; however, prolonged positive anomalies of 1°C during the warmest months are likely indicators of coral bleaching (Kenyon et al., 2006a; Kenyon and Brainard, 2006). Similar time-series analysis has been performed for data extracts from each of the 10 islands, atolls and special management areas. Results are provided in Appendix I.

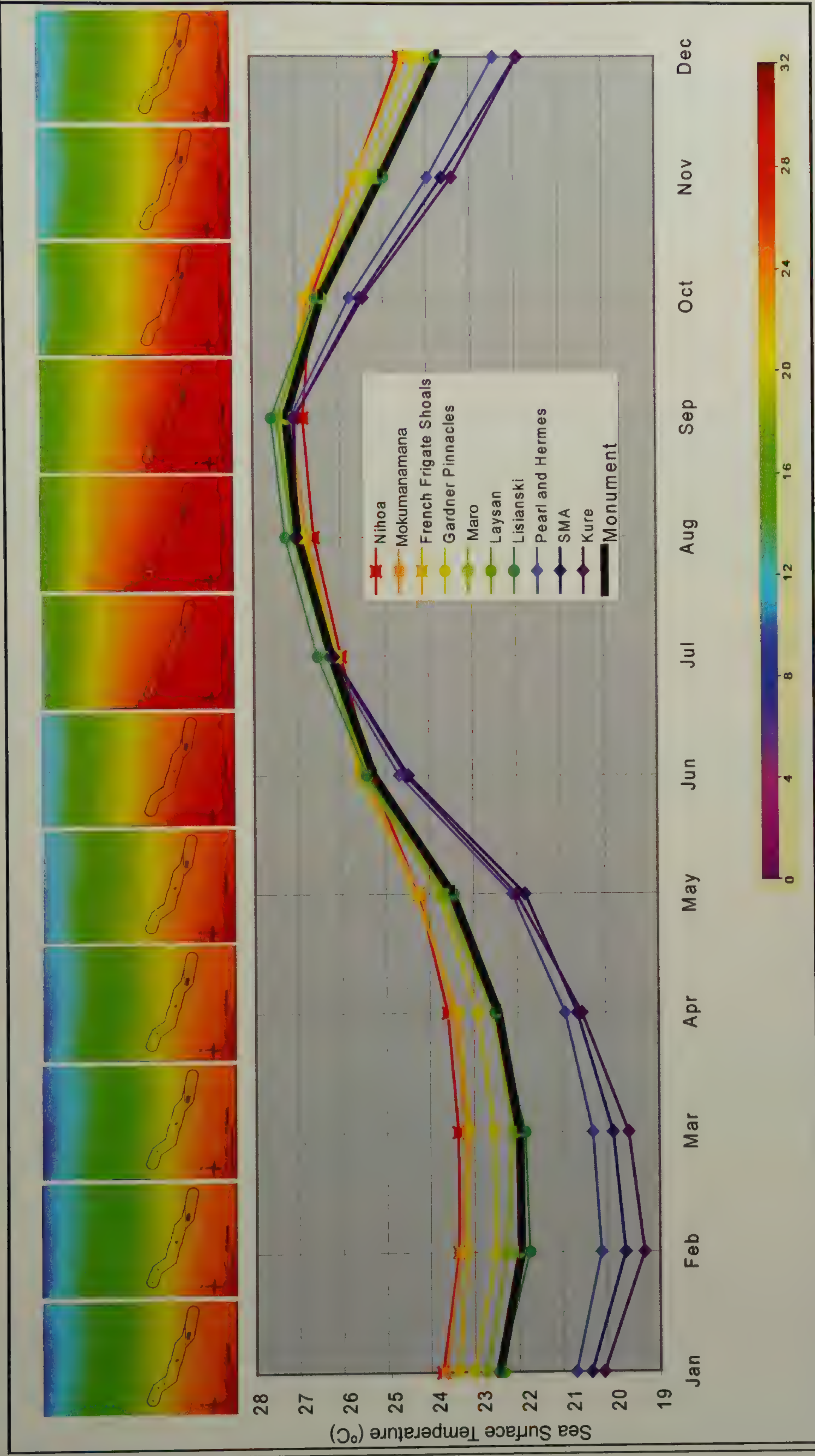


Figure 2.10. Long-term average monthly SST derived from NASA Pathfinder AVHRR. SST imagery for climatological monthly mean in Monument region. Time series ranges from 1985-2006.

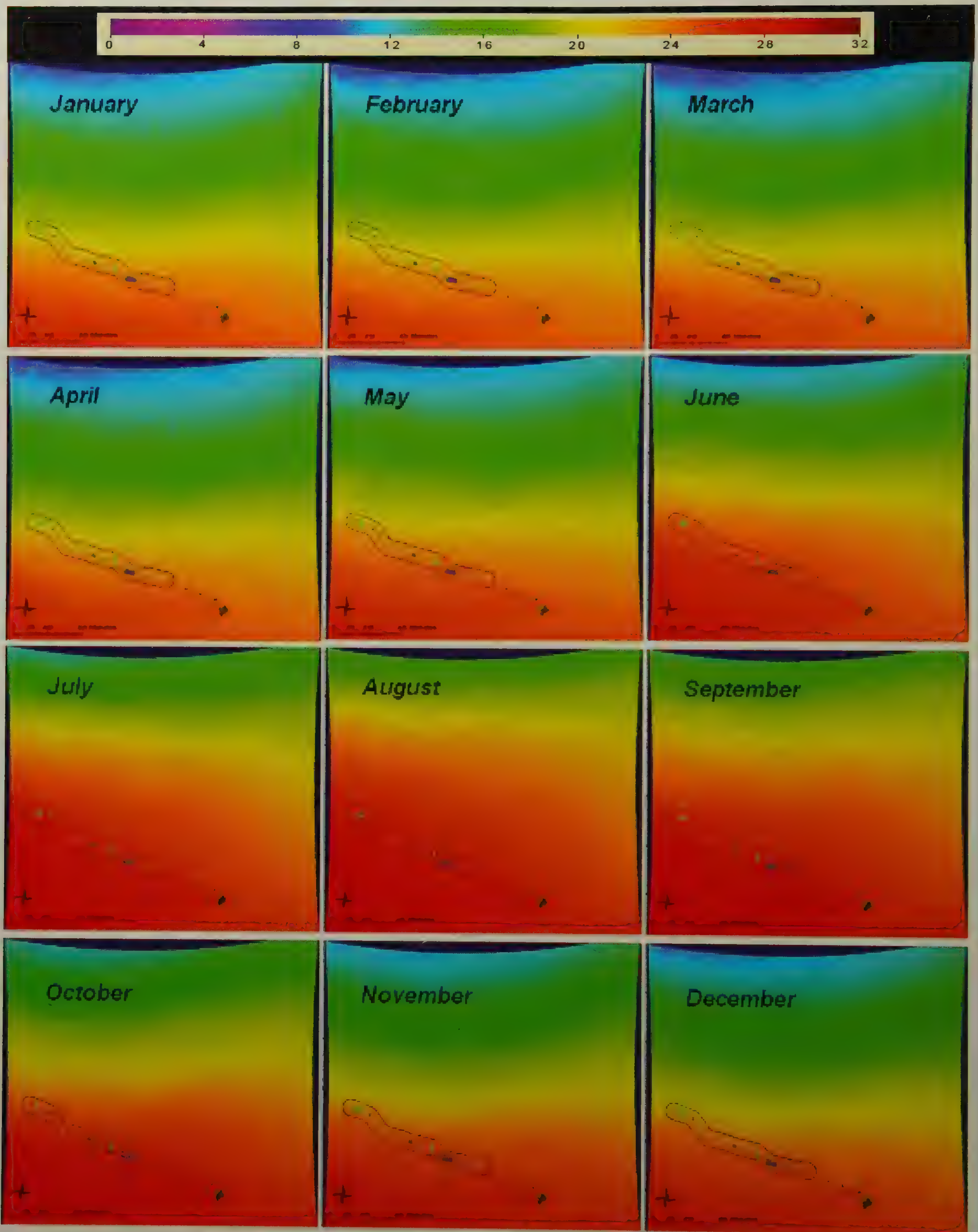


Figure 2.11. Monthly mean climatological SST, 1985-2006. Color bar is in degrees Celsius. Warm waters encompass the entire island chain in summer months but cooler waters intrude on the northern end of the Monument from November through May.

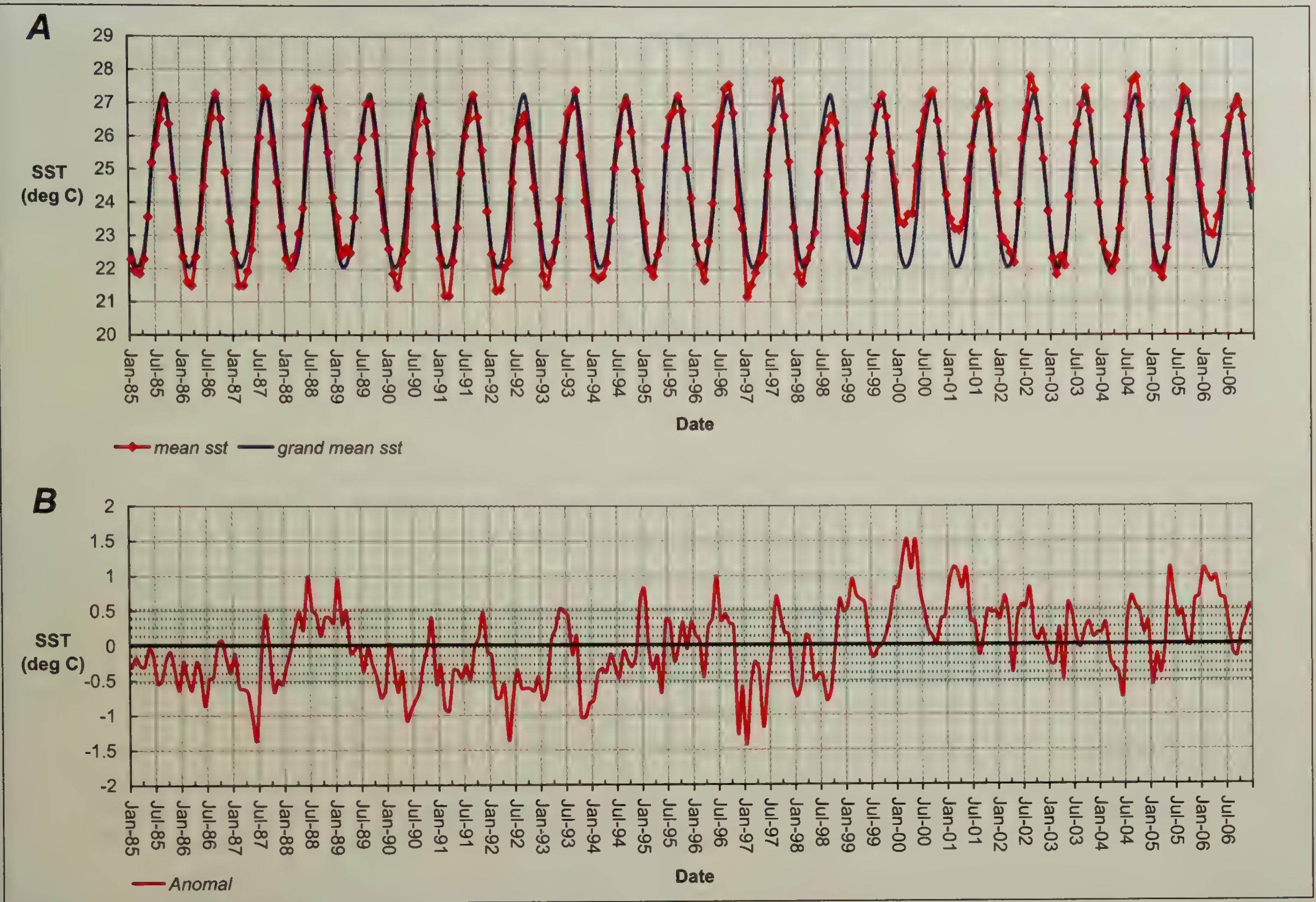


Figure 2.12. Panel A shows SST derived from NASA Pathfinder AVHRR imagery. Data from the entire Monument have been averaged to highlight temporal patterns from 1985 through 2006. Grand mean indicates the "climatological" average. Panel B shows temperature anomalies for the same period of record. Green bar indicates the range of one standard deviation of the anomaly time series. Peaks that fall above or below this range can be considered departures from "expected" anomalies.

NOAA led Pacific Reef Assessment and Monitoring Program expeditions to the NWHI documented the first recorded major bleaching events in the region. The NWHI were impacted by mass coral bleaching during late summer 2002 and again in 2004 principally due to a distinct region of higher than normal temperatures pervasive in the northern reaches of the Monument (Figure 2.13; Abey et al., 2003; Kenyon et al., 2006). No records of mass coral bleaching in the NWHI existed before this time. It was previously thought that the NWHI were less susceptible to bleaching due to the high latitude location whereas coral bleaching was documented in the MHI back in 1996 (Jokiel and Brown, 2004). During both events, bleaching was most severe at the three northern-most atolls (Pearl and Hermes, Midway and Kure), with lesser incidences of bleaching at Lisianski Island and farther south in the NWHI. SST data derived from both remotely sensed satellite observations as well as *in situ* buoys from the NOAA's Coral Reef Early Warning System suggest that protracted, elevated SST was a likely explanation for the bleaching response. This period of elevated SST coincided with a prolonged period of light wind speed, suggesting increased stratification due to decreased wave mixing of the upper ocean (Hoeke et al., 2006).

The time series analysis of SSTs data also suggests that two bleaching events may have occurred undetected in the summers of 1987 and 1991 (Figure 2.14). On these occasions, the northern atolls experienced temperature anomalies of 1°C or greater during the highest mean temperature months of August and September. Similar or larger positive anomalies have occurred in other regions and times but likely did not lead to coral bleaching because these events did not occur during peak temperature months.

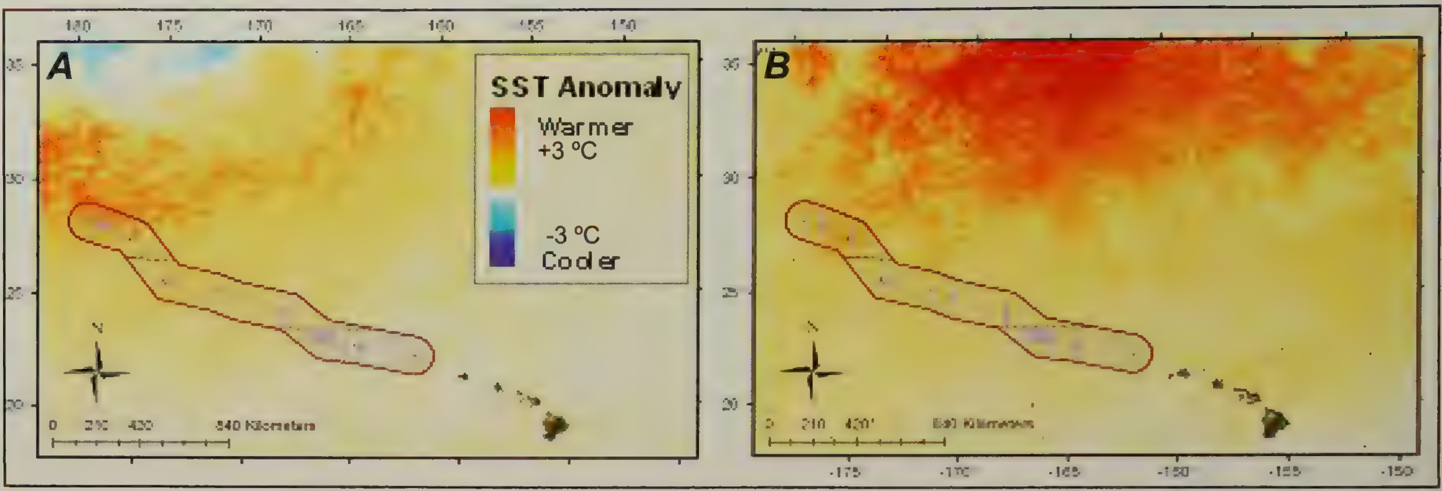


Figure 2.13. SST Anomaly images for August 2002 (A) and September 2004 (B). These periods of anomalously high SSTs in the northern atolls have been associated with coral bleaching. Source: NOAA GOES Imager.

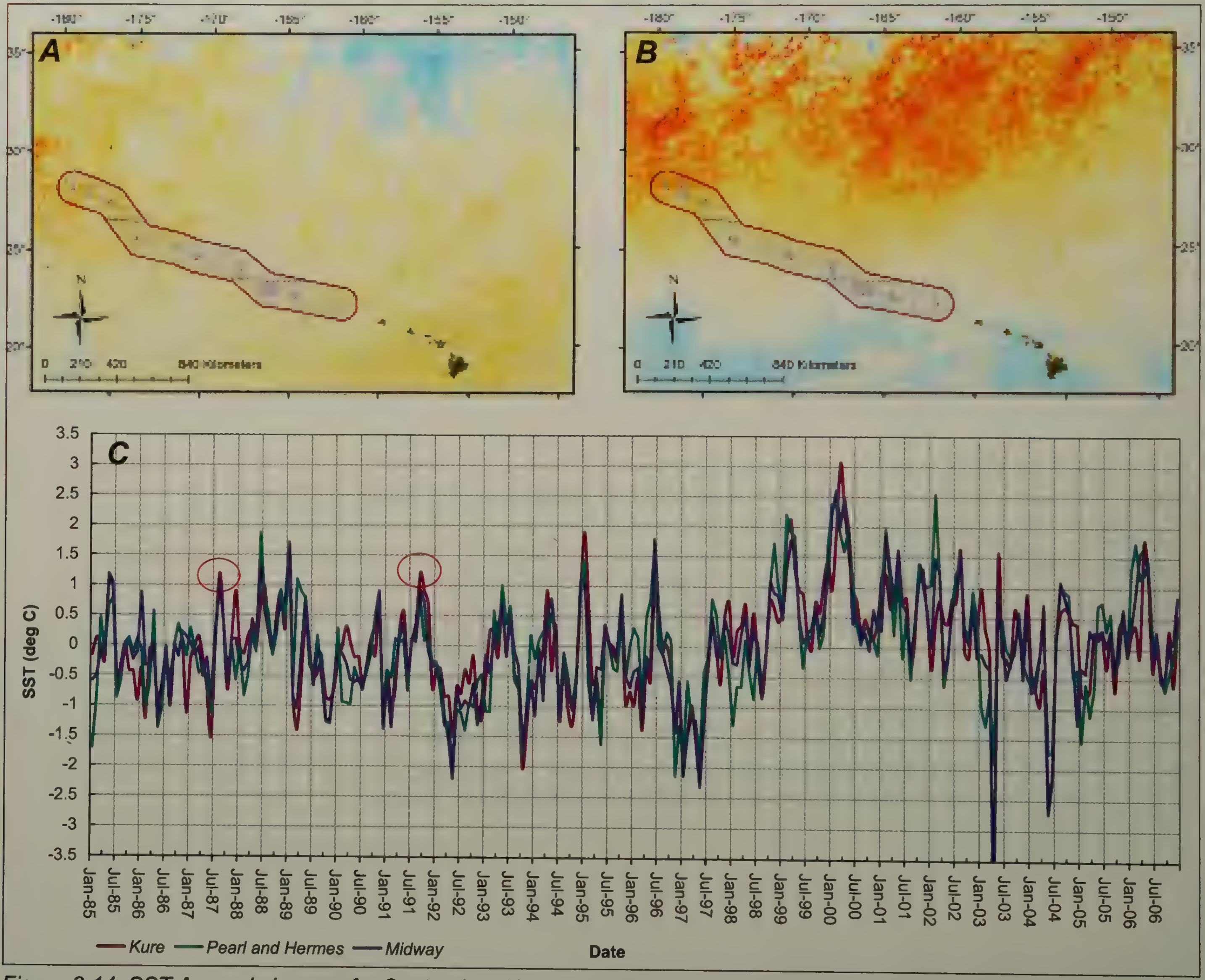


Figure 2.14. SST Anomaly images for September 1987 (A) and September 1991 (B). Distinct SST peaks in the northern atolls can be seen in the time series data (C).

Sea Surface Temperature Fronts

Bottom topography, ocean current confluence, variable wind stress and heat-water exchange across the sea surface produces patterns of vertical circulation, fronts or eddy-like motions that can affect biological distributions (Kazmin and Rienecker, 1996; Polovina, et al., 2001; Nakamura and Kazmin, 2003). Fronts are created by a variety of physical processes and have a wide range of biological consequences. A frontal system denotes areas of water mass convergence and usually produces zones of downwelling and upwelling flow. These vertical displacements have considerable ecological effects because environmental gradients, such as light, pressure, temperature, salinity, oxygen, nutrients, etc., are steepest in the vertical axis of the water column.

Vertical motion in fronts is often highly localized and can be easily identified with remote sensing techniques (Ullman and Cornillon, 1999). Areas with frontal activity tend to be areas of high biological activity (Polovina et al., 2001; Nakamura and Kazmin, 2003). The vigorous mixing of the water column at water mass confluence stimulates phytoplankton photosynthesis and sustains concentrations along the frontal zone (Savidge, 1976; Savidge and Foster, 1978). In response, zooplankton tend to concentrate along the fronts and are preyed upon by higher trophic groups. Marine birds, marine mammals and fish often aggregate at frontal areas as well. Tracking and catch studies have shown that key apex predators, swordfish, albacore tuna and loggerhead turtles, use these fronts for forage habitat on long distance migrations through the North Pacific (Bigelow et al., 1999; Laurs et al., 1984; Polovina, et al., 2001). Additionally, it has been shown that biological diversity is positively correlated with thermal fronts (Kazmin and Rienecker, 1996)

SST fronts are an important marine ecological feature for the overall eco-region of the Monument and the dynamic environment created by the fronts support many species that reside near or in the Monument. Large, persistent front generating regions are important for species transiting through the Monument during migration. However, front concentration within the Monument is relatively low, reaching highest levels in spring and primarily in the northern end of the Monument where the subarctic and subtropical gyres interact. Consistent with SST observations, SST frontal data indicate a seasonal patterned and latitudinal division within the Monument. Figure 2.15 illustrates the north-south movement of frontal concentration throughout the year. The northern region of the Monument experiences an active frontal season from December through April, usually with a peak in March. Even during the peak frontal probability period the southern region experiences few fronts. In mid-summer the frontal activity zone retreats far enough north that even the most northern atolls may not experience any significant fronts.

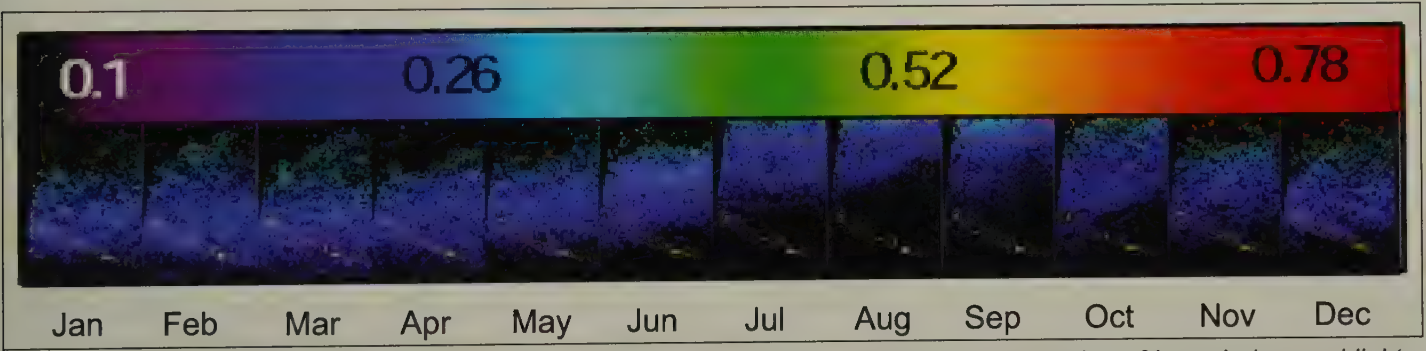


Figure 2.15. Average monthly sea surface frontal boundaries for the region. Dense clustering of boundaries, and lighter tones indicate elevated frontal boundary detection. Note higher frontal activity in the northern and western reaches of the Monument. Color strip denotes calculated frontal probability.

These pelagic habitats are poorly understood and warrant additional studies to improve the knowledge base for ecosystem management. It is possible with remotely sensed data to track these frontal zones over large, difficult to access regions through time. The interaction of these productive zones with the biota of the Monument may hold clues to long term sustainability of the Monument reef systems.

Chlorophyll

Chlorophyll concentrations are relatively low throughout the Monument, exhibiting oligotrophic characteristics common in open ocean environments. Even at these low levels, seasonal and latitudinal patterns are evident in both the chlorophyll images and the time series charts. The images shown in Figure 2.16 illustrates the temporal distribution of chlorophyll. This distribution is determined by the location of the convergence zones of the subarctic and subtropical gyres. A major area of productivity associated with this convergence area, referred to as the transition zone chlorophyll front (TZCF), contributes significantly to the variable productivity of the Monument region.

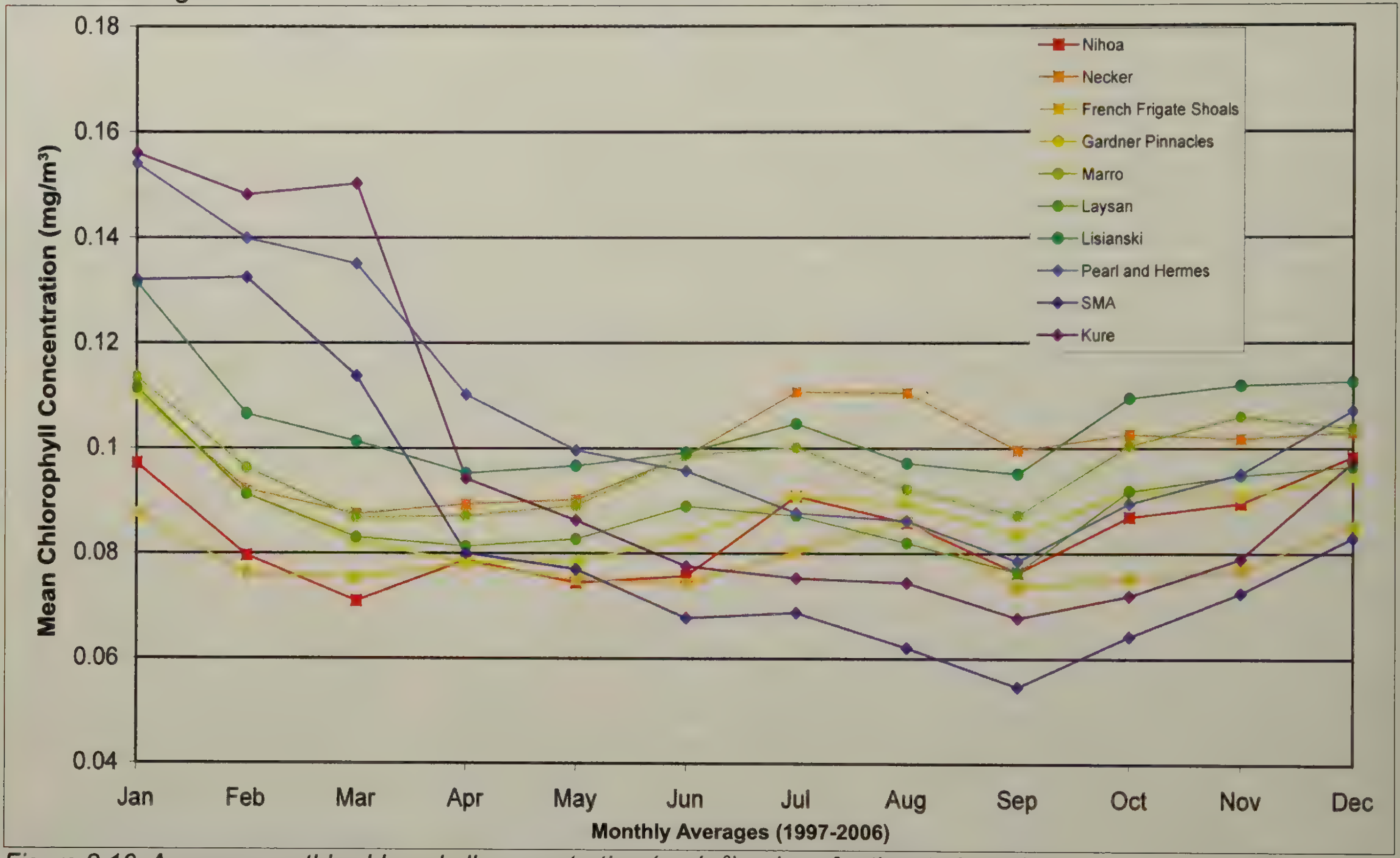


Figure 2.16. Average monthly chlorophyll concentration (mg/m^3) values for the study region.

The TZCF is a high productivity zone in the open ocean used by many species as an important feeding and migration zone. The TZCF has been identified as a chlorophyll concentration of approximately 0.2 μg/L or greater as measured from satellite (Polovina, 2005). The TZCF only rarely transits far enough south during its winter southerly shift to interact directly with the northern regions of the Monument. Even in these instances chlorophyll concentrations within the Monument generally do not reach as high as 0.2 □μg/L. However, both permanent and seasonal residents of the Monument do make use of this productive zone and more southern tracks of the TZCF have been correlated with higher fish catches in the Hawaiian Islands (Polovina et al., 2001). Coral reefs are also impacted by these occasional pulses of higher chlorophyll through population increases of the coral eating sea star, *Acanthaster planci* commonly known as the crown-of-thorns sea star (Hoeke et al., 2006). These periodic increases in productivity within the Monument likely have meaningful consequences to management of the atolls and reefs of the Monument.

Mean chlorophyll concentrations have cyclical temporal variability. Higher chlorophyll concentrations move south into the Monument boundaries during the winter months and retreat far north in the summer. The northern region experiences the largest variability in mean concentration from high season to low season ranging from highs of nearly 0.18 μg/L to lows below 0.06 μg/L. The central and southern regions exhibit a more constant environment with chlorophyll concentrations ranging between 0.07 and 0.11□ μg/L. In addition to seasonal changes, the northern regions also exhibit high interannual variability in chlorophyll concentrations. The northern atolls experienced very low concentrations of chlorophyll in 1999, 2000 and 2001, but also relatively high concentration years in 1998, 2003, 2004 and 2005 (Figure 2.17). Note that even the highest mean monthly chlorophyll concentration is below the threshold of 0.2 µg/L used to identify the biologically active TZCF. Time-series analysis has been performed for chlorophyll data extracts from each of the analysis regions, and results are provided in Appendix II.

While these values are low relative to coastal continental chlorophyll concentrations, these chlorophyll blooms offer sustenance to support a diverse community around the atolls of the Monument. The southern atoll group exhibits little variance through time and can be characterized as having generally low chlorophyll concentrations, usually between 0.06 and 0.09□ µg/L. The central region exhibits slightly higher variability and a broader range in chlorophyll concentrations when compared to the south, likely owing to its position as a transition zone between the subarctic north and the subtropical south.

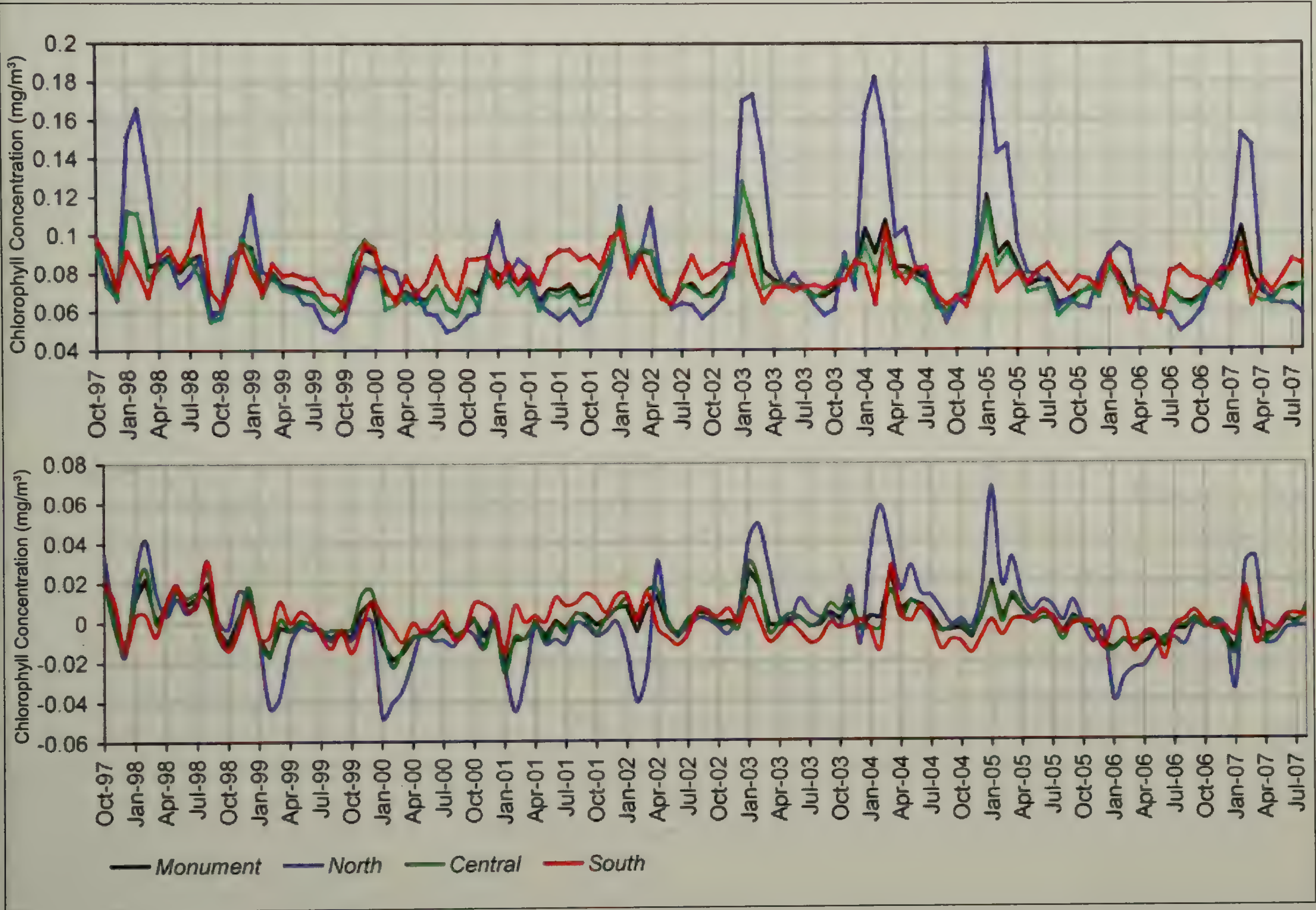


Figure 2.17. Time-series for chlorophyll (top) and chlorophyll (mg/m³) anomaly (bottom) in each analysis region of the Papahanaumokuakea Marine National Monument (1997-2006). Source: SeaWiFS.

Trends in chlorophyll concentration anomalies can be correlated with the PDO and ENSO via the multivariate ENSO index (MEI). Chlorophyll concentrates in the more northern atolls are positively correlated with the PDO index (ρ=+ 0.404) where as the southern atolls are negatively correlated (ρ=-0.02). The rank correlation compares the relative size and direction of the indicators. For example, in the northern regions from 1998-2002, relatively strong cool phase PDO index values (negative) are positively correlated with periods of relatively low chlorophyll concentration anomalies (Figure 2.18). This correlation is expected as a cool phase PDO is typically indicated by higher SSTs in the north central Pacific (Mantua et al., 1997), and warmer SSTs are associated with lower levels of chlorophyll production. An inverse relationship between chlorophyll concentrations and the PDO index in the southern atolls is explained by the typically cooler tropical waters in the eastern Pacific during cool phase PDO and the association of higher chlorophyll counts and cooler waters. Additionally, PDO effects are primarily seen in the more northern latitudes (Mantua et al., 1997), so an increasing strong relationship with increasing latitude is not entirely surprising.

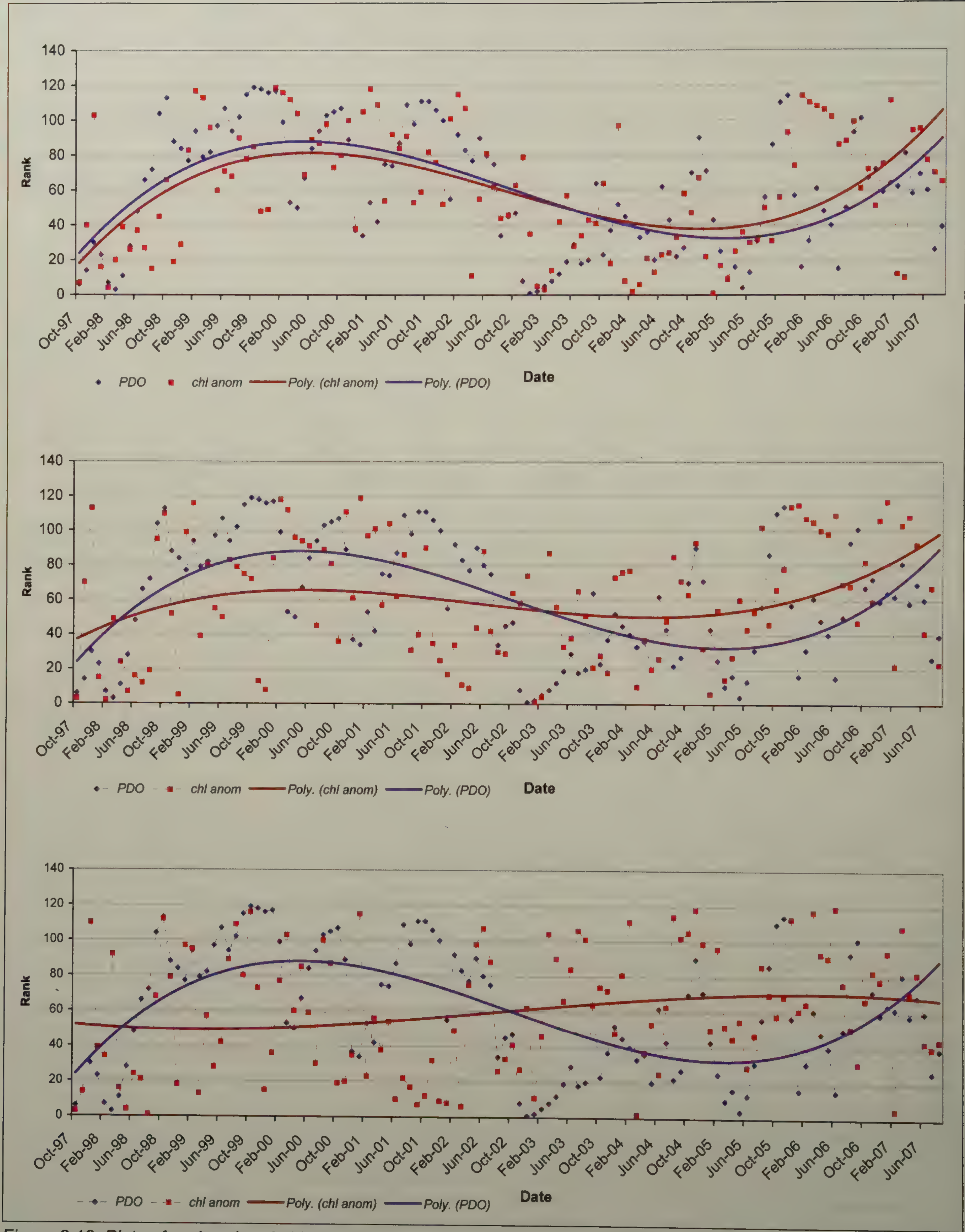


Figure 2.18. Plots of rank-ordered chlorophyll anomaly and PDO Index 1997-2007 values for the northern (top), central (middle) and southern (bottom) regions of the Monument. Lines represent non-linear trends through the time-series to highlight the degree and nature of correspondence. Poly is a 3rd order polynomial fit through each time-series (trend).

Six El Niño events occurred during the time series analyzed here, including: 1987, late 1991- early 1992, late 1997-early 1998, late 2002-early 2003, late 2004-early 2005 and late 2006 (National Weather Service, 2007). The 1997-1998 was possibly the most intense in the 20th century; however, the northern region of the NWHI were more strongly influenced by the weaker events of 2003, 2004 and 2005. This is possibly due to interactions between PDO and ENSO. The El Niño events are evident in the SST time series throughout the Monument but are particularly apparent in the chlorophyll time series of the northern atolls. The 1997-1998, 2003, 2004 and 2005 El Niños led to much higher chlorophyll concentrations than normal in the northern half of the Monument. During El Niño events, the Aleutian Low pressure system is more intense and extends south into the Monument region, resulting in stronger winds, more mixing and cooler SSTs (Bromirski et al., 2005). La Niña phases of ENSO show opposite characteristics in the Monument region leading to warmer waters and lower chlorophyll concentrations. La Niña events occurred in 1988, early 1989, and late 1998-2000. The La Nina events produced slight decreases in chlorophyll, but not of the magnitude of increase seen in the El Niño years.

Wind

Winds of the NWHI are generally dominated by the Trades, a persistent system that blows from the northeast to the southwest. These winds move from the Americas to Asia between the equator and 30oN, and are remarkably consistent throughout the year. Meridional variability is relatively weak and is dominated by Coriolis Forces which set up the North Pacific Gyre. Meridional winds are defined as the directional component along the local meridian, and are positive if from the south, and negative if from the north. Likewise, the zonal wind component is positive if it blows from the west and negative if from the east (i.e., Westerlies). An analysis of wind data (1985-present) revealed strong NWHI zonal variability in the NWHI, and three distinct components in the region.

The southerly portion of all monthly wind climatologies – from 15ºN to approximately 30ºN – is dominated by the trade winds which are associated with warmer air and the Pacific High Pressure System (Figure 2.19). North of the trade wind zone is a transitional area extending from approximately 30ºN to 40ºN of weak variable winds known as the North Pacific Doldrums, which ancient mariners referred to as the "Horse Latitudes". In the northern portion of the study area (above 40°N), winds prevail out of the west southwest, which is associated with cooler air and dominated by the Aleutian Low pressure system. The location of the three respective areas migrates north and south seasonally, and is a major forcing function of regional oceanographic conditions. In addition to the analysis of monthly winds described above, average annual winds were calculated and analyzed for the study area. Most years exhibited only modest changes in interannual variability. The one notable exception was the intense El Niño event of 1997. Figure 2.20 shows the annual mean wind vectors from 1996, 1997 and 1998, sequentially. The Trade Winds in the annual mean of 1997 a near full directional reversal. In 1996 and 1998 the Trade Winds were out of the east northeast, as expected. In 1997; however, the winds were strongly blowing out of the south southwest. Also notable is that the general circular pattern of the winds, which typically form a gyre in the North Pacific, were absent. Throughout the analyzed region winds were out of the southwest which is a drastic difference from all other calendar years analyzed (1985-2007). 1997 also showed remarkable zonal variability along 30ºN. West of -170º the magnitude of the winds were much less than they were to the east.

Circulation around the high pressure is clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. The high pressure in the center is due to the westerly winds on the northern side of the gyre and easterly trade winds on the southern side of the gyre. These cause frictional surface currents towards the latitude at the center of the gyre. The buildup of water in the center of the gyre creates equatorward flow in the upper 1,000 to 2,000 m of the ocean, through rather complex dynamics. This equatorward flow is returned poleward in an intensified western boundary current. The North Pacific Gyre comprises most of the northern Pacific Ocean, and occupies an area of approximately 34 million km². The Gyre has a clockwise circular pattern and comprises four prevailing ocean currents: the North Pacific Current to the north, the California Current to the east, the North Equatorial Current to the south, and the Kuroshio Current to the west.

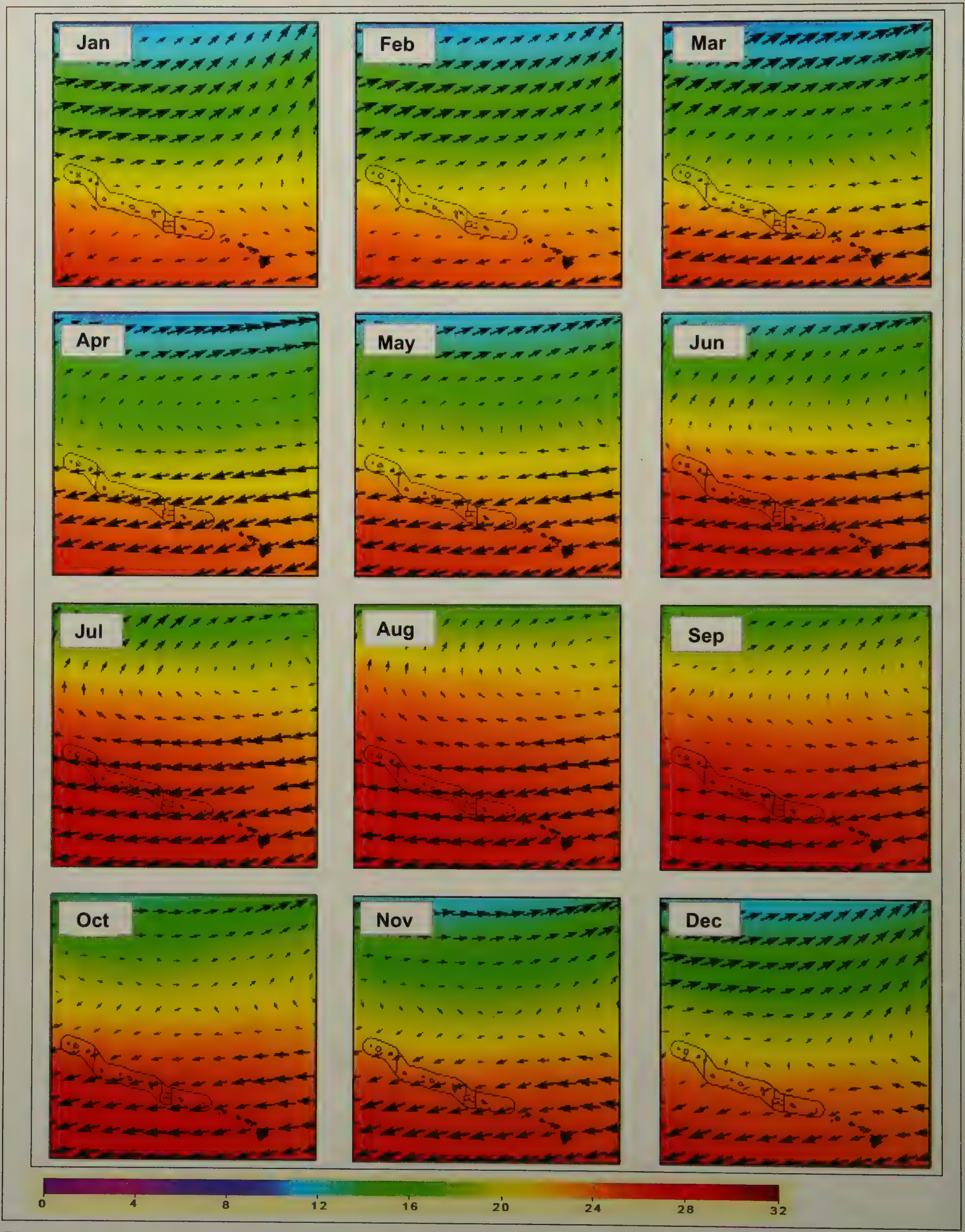


Figure 2.19. Long-term averaged monthly climatological wind data from 1948 through 2007 from the NCEP Reanalysis winds. Wind field data are superimposed on a false-color image of average monthly SSTs (warm tones=warm water, cool tones=cool water). Arrow size denotes relative wind strength. Source: AVHRR climatology.

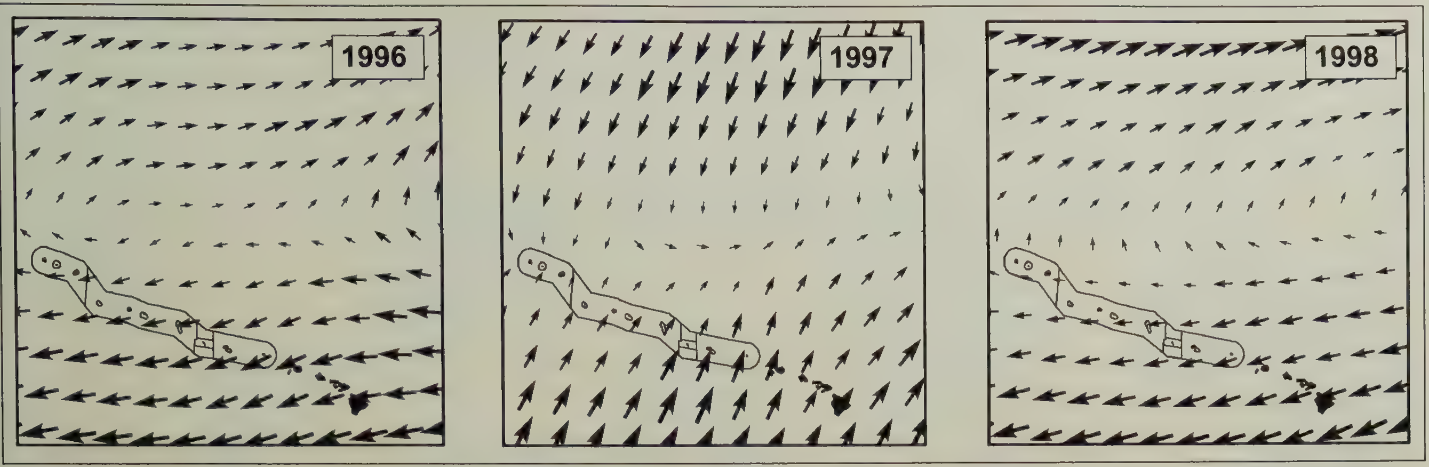


Figure 2.20. Three examples of annual means (1996, 1997 and 1998) from the NCEP Reanalysis winds. The El Niño event from 1997 shows relatively drastic variability from the preceding and subsequent years. Arrow size denotes relative wind strength.

Sea Surface Height and Currents

The height of the sea surface is determined by the mass of water at a given location and by the water's density (a function of temperature, salinity and pressure). Space based altimeters such as the Jason and Topex/Poseidon missions measures changes in SSH due to both of these factors - redistribution of mass and changes in density. On seasonal to interannual time-scales, density changes are the largest contributor to sea level variability. In the tropics they are the dominant one (Gilson et al., 1998).

Ocean currents can increase SSH by up to a meter higher over the surrounding area. Currents can therefore be mapped by measuring height variations. A view of the global ocean circulation shows currents circulating around elevations and depressions in SSH. Currents flows around positive SSH in a clockwise direction in the Northern Hemisphere, and in a counterclockwise direction around negative SSH (the opposite occurs in the Southern Hemisphere). Figure 2.21 shows an example AVISO derived SSHA image for the study region during December 2005. Warm tones indicate regions of surface height elevation, while cool tones highlight surface depressions. Current vectors derived from SSHA are superimposed on the image to show modeled surface currents (geostrophic flow). As described, note the counterclockwise rotation around the blue tones.

Numerous studies have summarized the positive association between SSH maximums and SST maximum in open ocean environments (Jones et al., 1998; Wilson and Coles, 2005; Fu 2004). Given the setting of the Monument in the middle of the Pacific Ocean, it is therefore not surprising that SSHA patterns correlate with SST seasonal patterns. The difference between the measurements is that SSH are more a measure of the heat (energy) that is stored in the ocean below while SST is a surface measurement that tells us about interactions with the atmosphere on a more immediate time scale (JPL). The ocean energy below the surface reflected in the SSHA influences surface events over much longer periods and areas.

Localized and episodic SSHA events can be attributed more readily to wind events (Di Lorenzo et al. 2008; http://www.ig.utexas.edu/research/projects/od_sst/) but larger regional SSHA patterns are clearly tied to SST. The direct influence of SSHA on the atolls of the Monument can be found in generation of winds and a current related to transient local eddies and fronts (Seki et al., 2002). Mesoscale SSHAs can be used to identify areas of convergence that can indicate upwelling and productive ocean zones concentrating and attracting species throughout the food web (Seki et al., 2002). These mesoscale features are embedded in larger scale frontal zones that scan large quadrants of the Pacific Ocean and change over periods of months and years. The PDO is a long period ocean feature reflected in SSHA. The PDO waxes and wanes between cool and warm phases approximately every five to 20 years. In the cool phase, higher than normal SSH caused by warm water form a horseshoe pattern that connects the north, west and southern Pacific, with cool water in the middle (JPL). The NWHI lie along the typical boundary between cool and warm waters during a cool phase PDO.

SSHAs in the Monument do have a seasonal signal with higher anomalies occurring in late summer and lows in the spring (Figure 2.22). The regional differences observed in the other oceanographic factors are not as pronounced with SSHA. The northern regions do experience a less pronounced swing in anomalies from high season to low season.

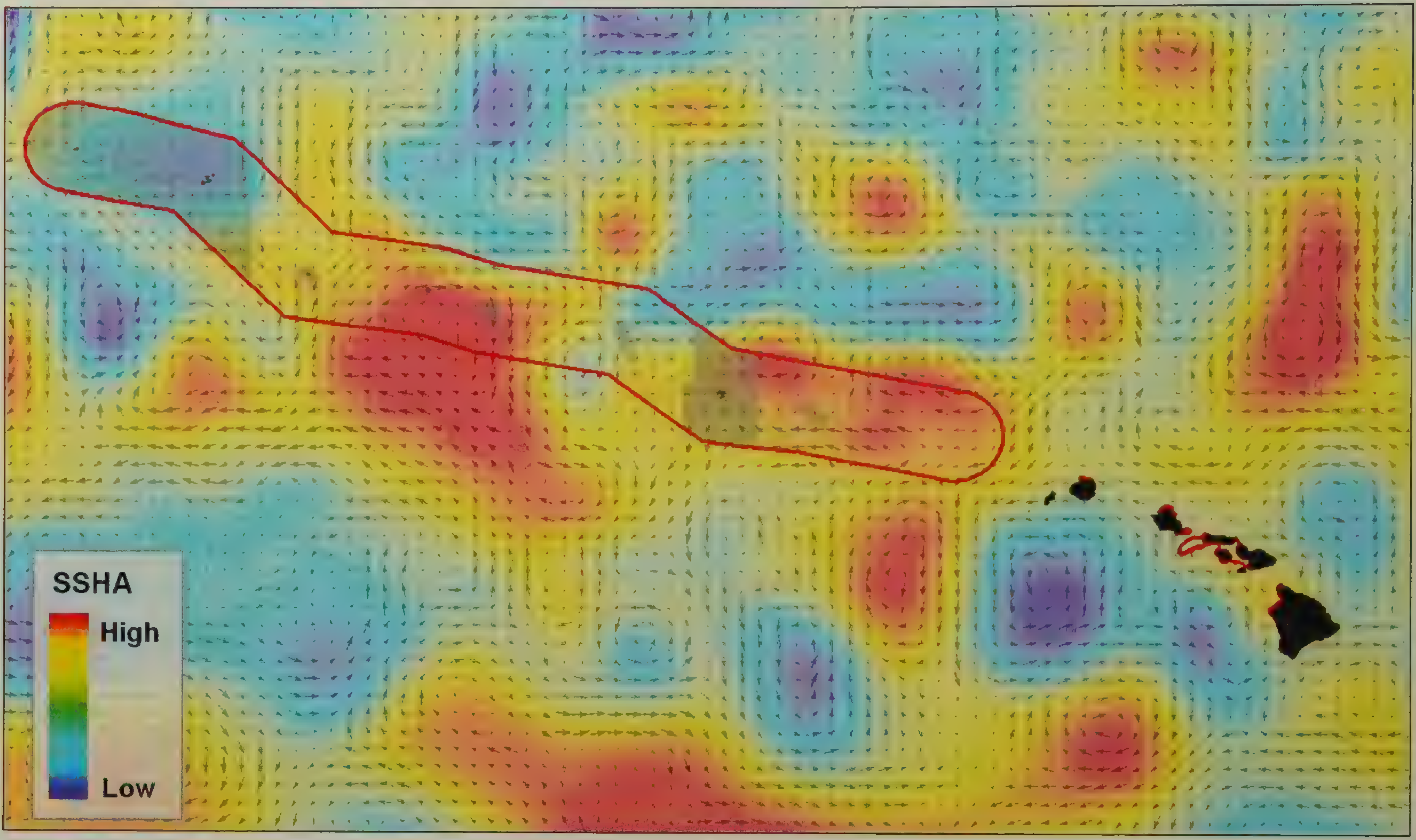


Figure 2.21. Example sea surface height anomaly image and associated surface currents in the study region (December 2005). Red tones indicate "peaks", while blue tones indicate "valleys", and arrows indicate direction of flow. Muted polygons delineate Monument "Special Protection Areas".

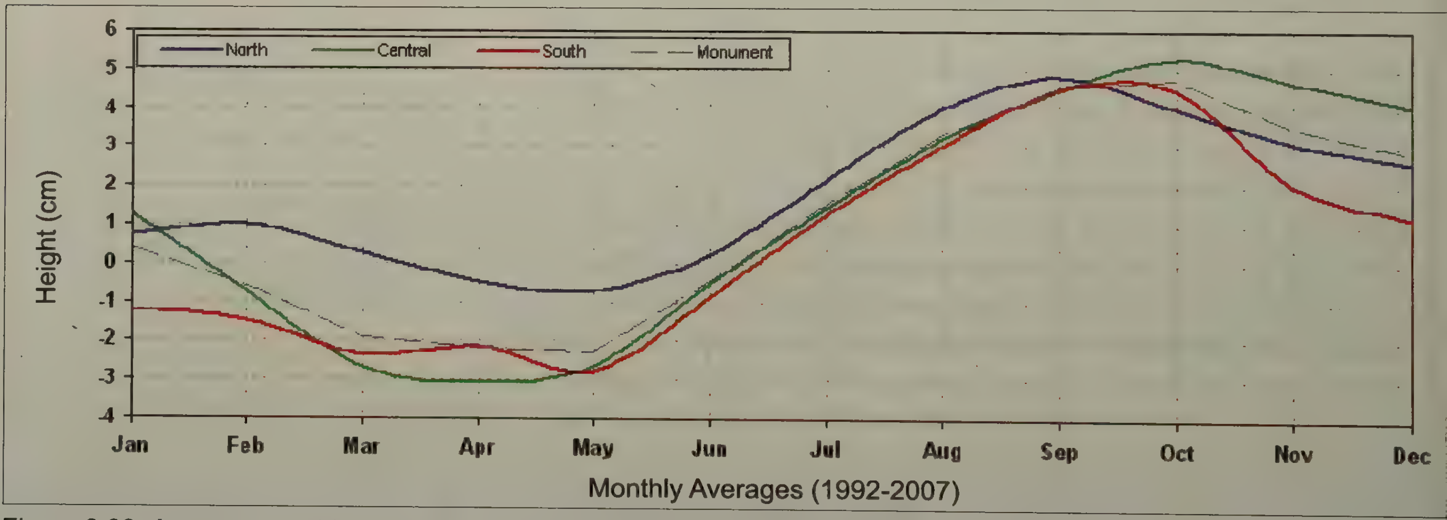


Figure 2.22. Average monthly sea surface height anomaly (cm) for each region in the Monument.

EXISTING DATA GAPS

Overall there is a need for basic information on spatial and temporal patterns of water movement, quality and characteristics within the NWHI at a range of scales. Moving forward it is important for resource managers to have a unified hydrodynamic model to describe connectivity, identify seasonal areas of oceanographic productivity, detect change in the pattern and scales of movement, dispersal and recruitment of living resources at various life stages, identify and document variability in larval and nutrients sources, understand debris dispersal and establish management units within the NWHI. Specific opportunities include research to improve the understanding of:

- carbon, nitrogen and phosphorus in the ecosystem and the transfer to higher trophic levels;
- community changes that will result from alterations to reef structure by major ocean/atmosphere events;
- discerning anthropogenic impacts from natural variability of the physical ocean environment;
- PDO/ENSO events and effects;
- geomorphological and sedimentalogical processes affecting reefs and terrestrial areas;
- dispersion patterns of key pollutants; and
- physical and biological effects of extreme events on the ecosystem.

CONCLUSIONS

The Monument is a unique open ocean ecological observatory, relatively free from the activities of humans and so large it encompass multiple overlapping and interacting marine ecosystems. The Monument's position near the shifting boundary of the oligotrophic North Pacific Central Gyre and the productive waters of the North Pacific Subpolar Gyre makes it an ecosystem that is influenced directly by climate systems that vary greatly in time, over years and decades, and space, over hundreds of kilometers. The atolls and islands are subject to typical yearly seasonal patterns as well as the larger climactic cycles of the PDO and the ENSO.

The ecosystems of the Monument are linked by these circulation patterns but are also stratified by their distance from the frontal zone where the gyres meet. There are three latitudinal groups within the Monument bounds. The northern group, Kure, Midway and Pearl and Hermes; the central group, Lisianski, Laysan, Maro Reef and Gardener Pinnacles; and the southern group, French Frigate Shoals, Mokumanamana and Nihoa. These groups exhibit similarities in all the factors that were examined. The environmental factors examined in this report are all directly impacted by the changes in the basin wide circulation system. These linkages happen over monthly, seasonal, annual and longer term climactic time intervals. Examination of chlorophyll-a, SST, SST fronts, and SSHA over climatological and monthly periods make it clear that these factors are linked.

In addition, these factors correlate with patterns and changes in climactic scale events such as the PDO and ENSO. These large-scale oceanographic forcing mechanisms change the characteristics of water temperature and productivity across the Pacific, and have a significant effect on the habitat range and movements of pelagic species in the NWHI. Tuna are often concentrated near islands and seamounts that create oceanographic divergence and convergence zones, which in turn tend to concentrate forage species (PMNM, 2008). Swordfish and numerous other pelagic species tend to concentrate along food-rich temperature fronts between cold upwelled water and warmer oceanic water masses (Polovina et al., 2001). These frontal zones also have been determined to function as migratory pathways for loggerhead sea turtles (Polovina et al., 2001, 2004).

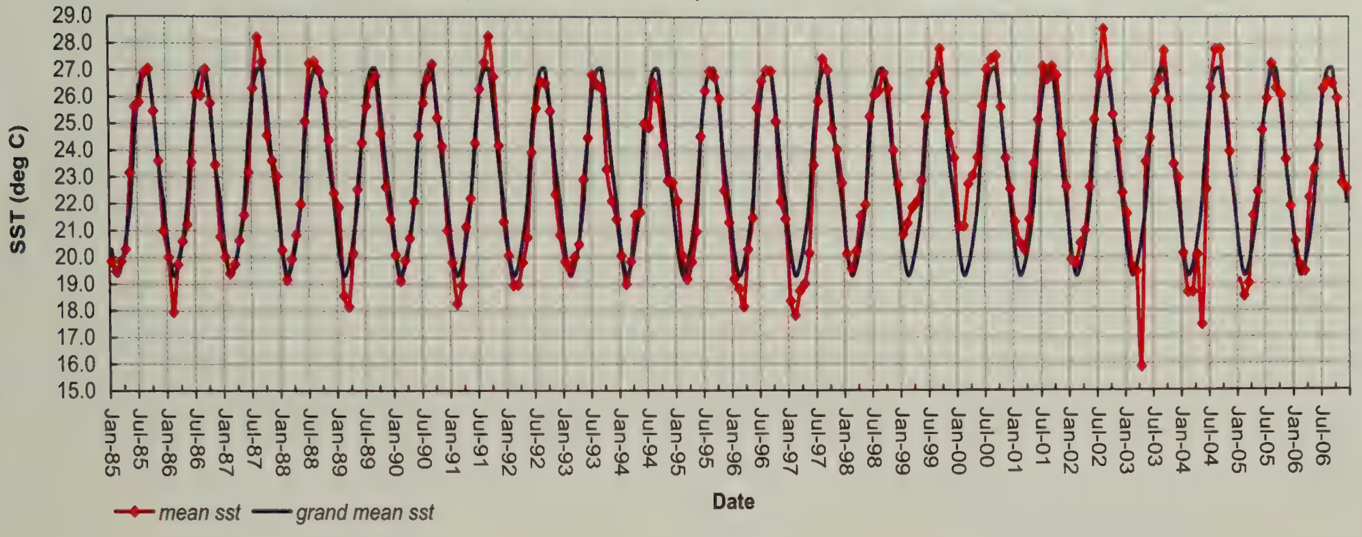
Hundreds of thousands of seabirds breed in the Monument and are primarily pelagic feeders. The fish and squid they consume are generally associated with schools of larger predatory fish described above. While both the predatory fish and the birds are capable of foraging throughout their pelagic ranges (which encompass the entire Monument and tropical Pacific Ocean), the birds are most successful at feeding their young when they can find schools of predatory fish within easy commuting range of the breeding colonies (Ashmole, 1963; Feare, 1976; Flint, 1991).

Recent analyses of SeaWiFS remotely-sensed ocean color data shows an expansion of low productivity ocean water worldwide (Polovina et al., 2008). This expansion of low chlorophyll water has reached the Hawaiian Archipelago and has implications for the productivity of the entire ecosystem. These oligotrophic areas are expected to continue to expand with future global warming forcing (Polovina et al., 2008).

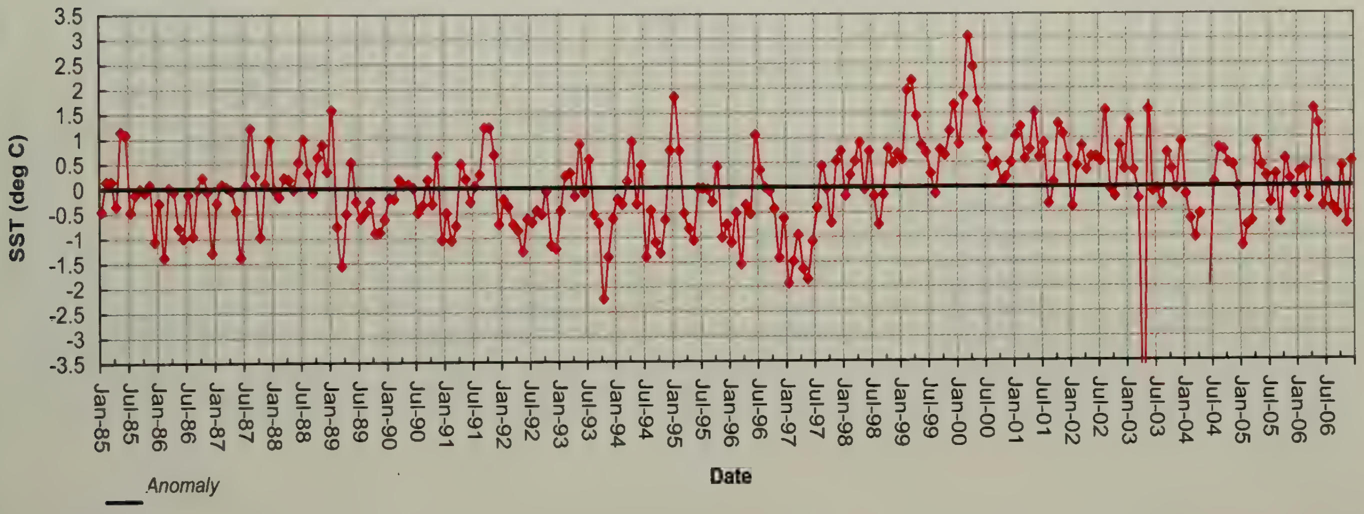
While there is well documented small-scale (i.e., local) variation in population structures (Ashmole and Ashmole, 1967; Boehlert, 1993; Johannes, 1981), the large-scale patterns in oceanography described in this chapter provide a dominant force in modulating these populations. Finer-scale, stochastic processes also operate within this climate driven construct. It is important to note that these processes cannot easily be resolved using remote sensing technologies (e.g., wind wakes, wake eddies, etc.), yet are what likely produce pelagic "habitat" conditions that attract individuals and sub-populations to a given region, island, atoll or pinnacle. The following chapters featured in this document will provide a more detailed view of the abundance, distribution and temporal "behavior" of biological populations inhabiting the NWHI.

APPENDIX I. SEA SURFACE TEMPERATURE (AND RELATED) TIME SERIES PLOTS

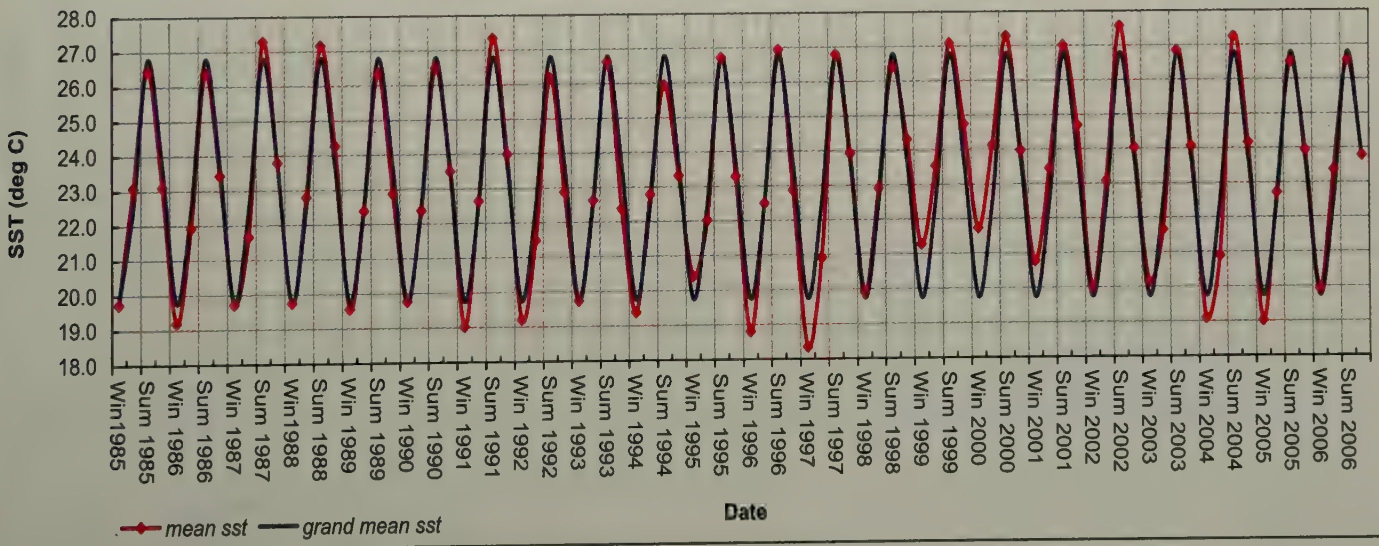
Monthly Mean Sea Surface Temperature for Kure Atoll 1985-2006

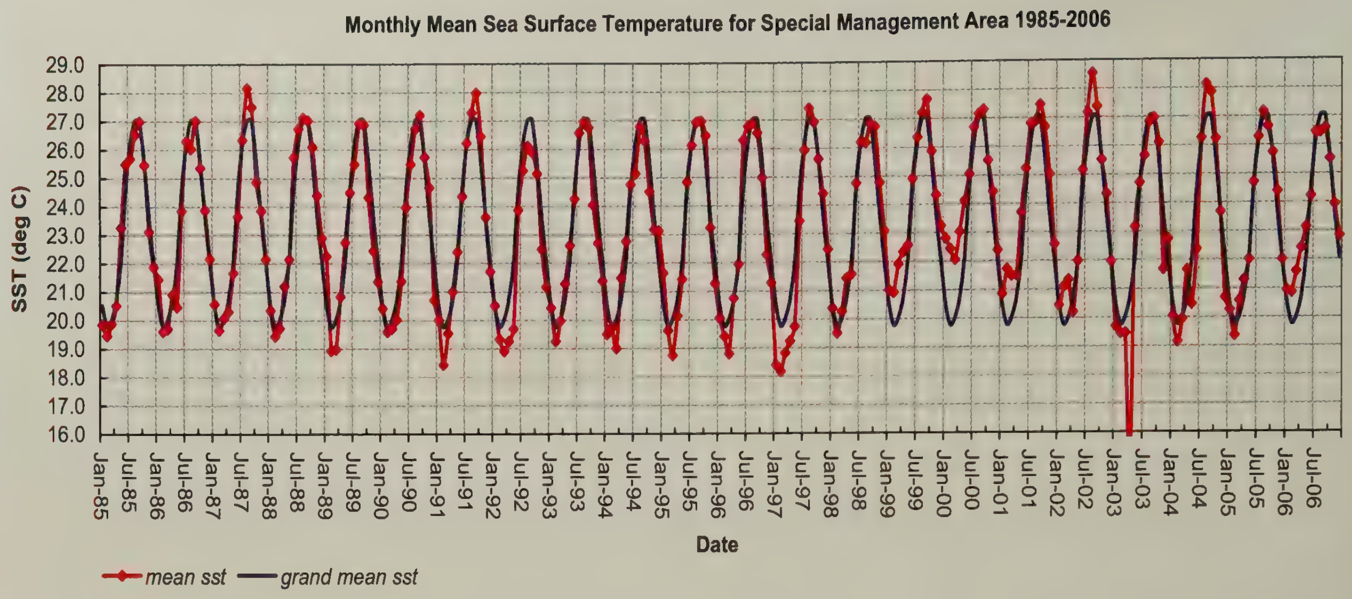


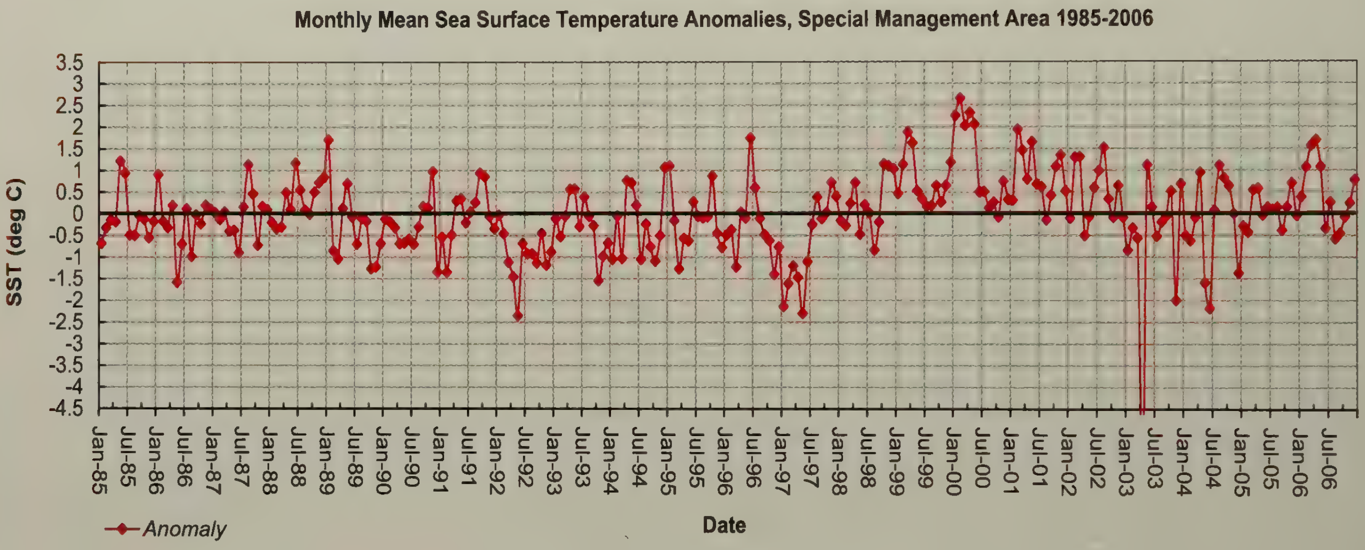
Monthly Mean Sea Surface Temperature Anomalies, Kure Atoll 1985-2006

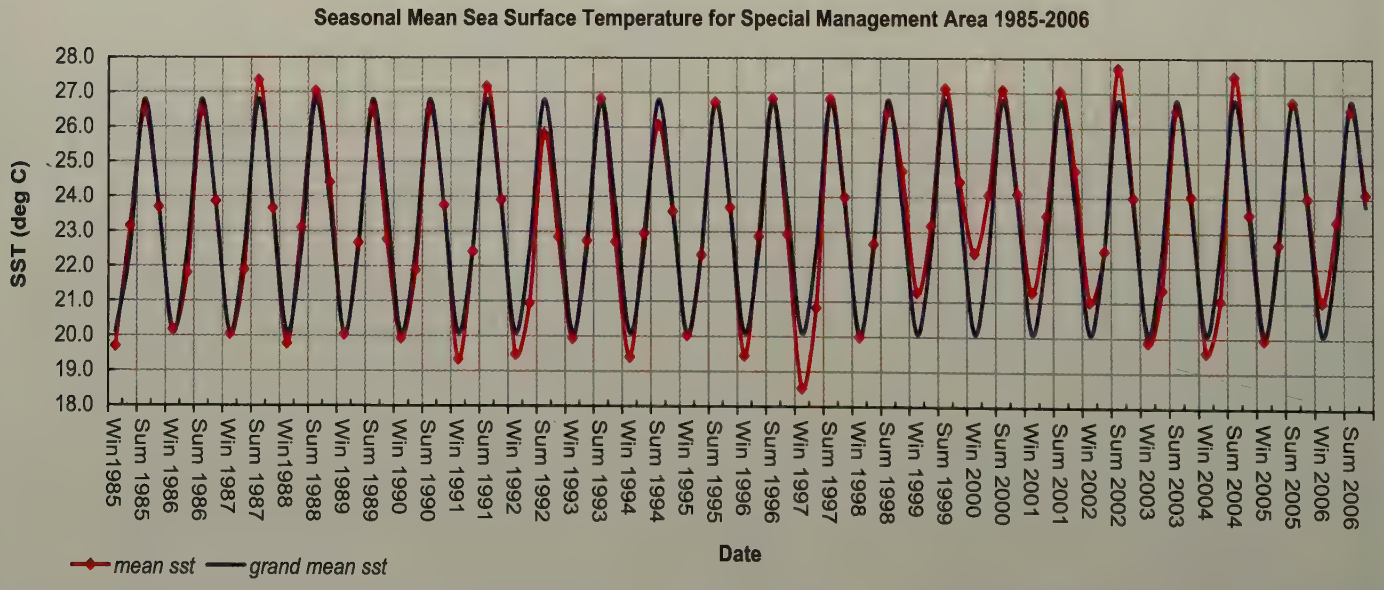


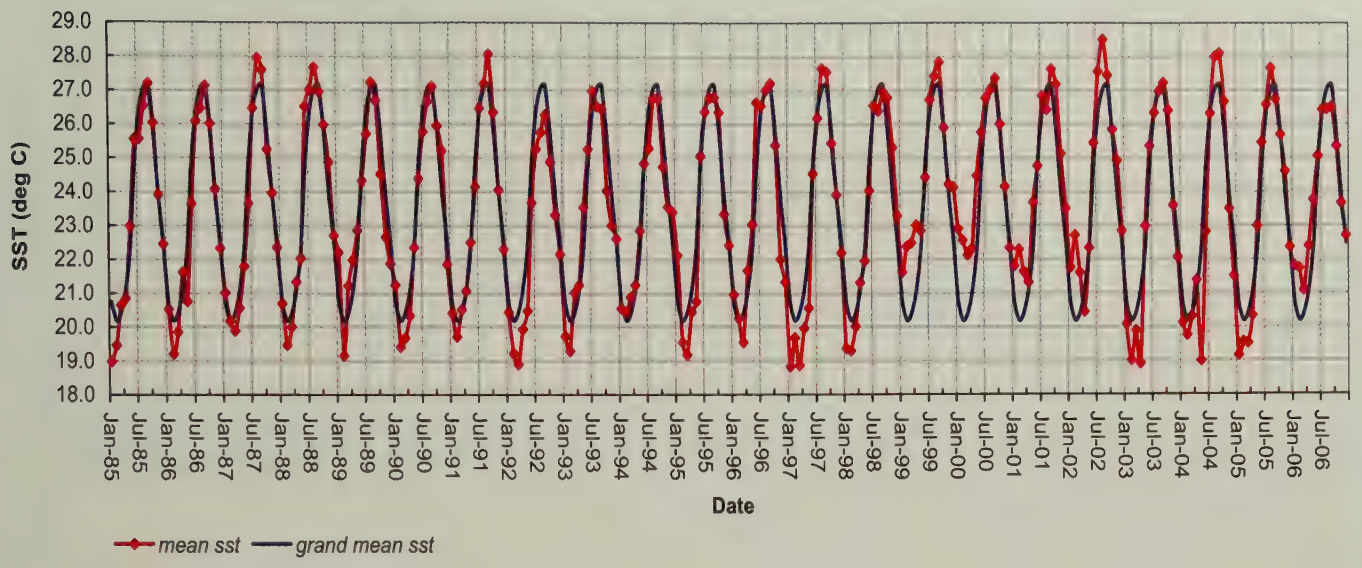
Seasonal Mean Sea Surface Temperature for Kure Atoll 1985-2006



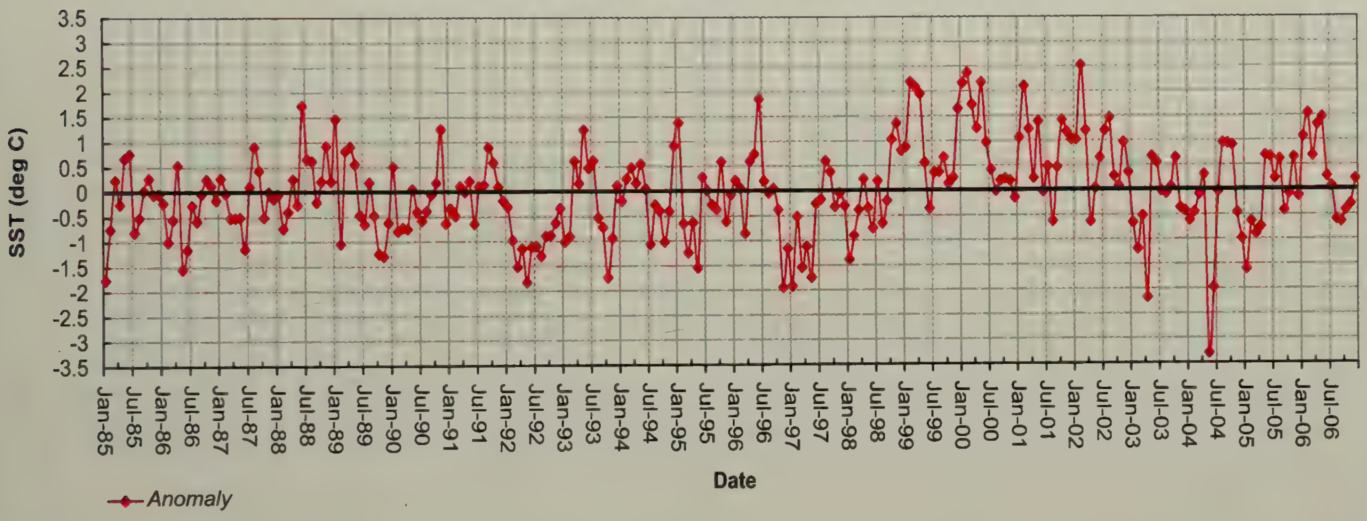

Monthly Mean Sea Surface Temperature for Special Management Area 1985-2006


Monthly Mean Sea Surface Temperature Anomalies, Special Management Area 1985-2006

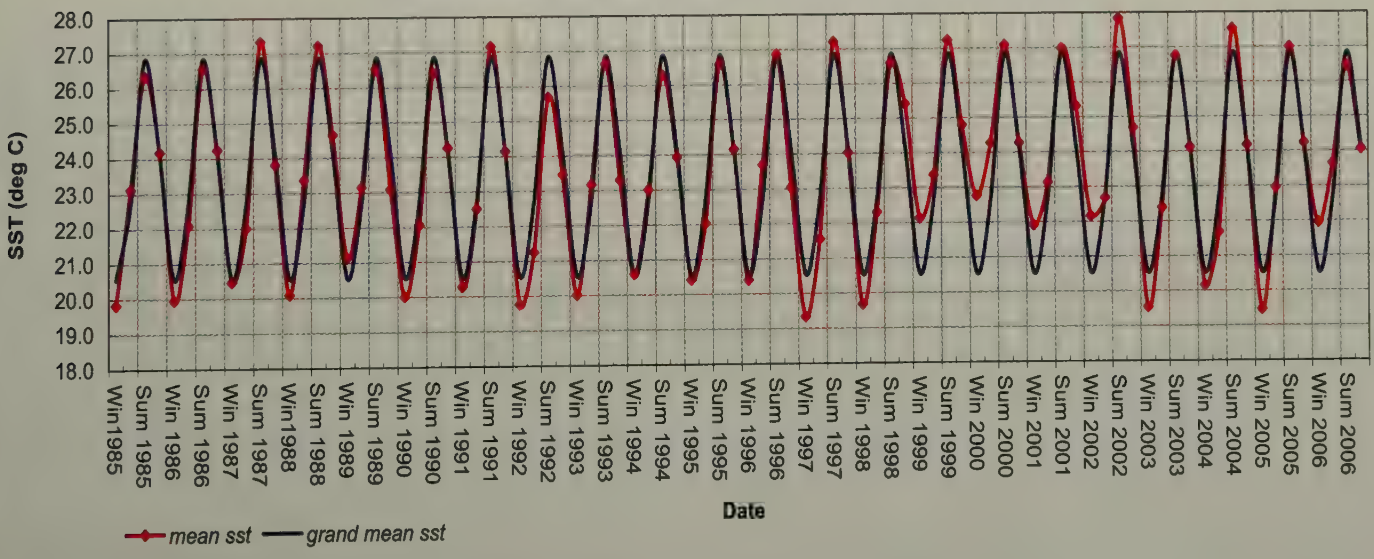

Seasonal Mean Sea Surface Temperature for Special Management Area 1985-2006



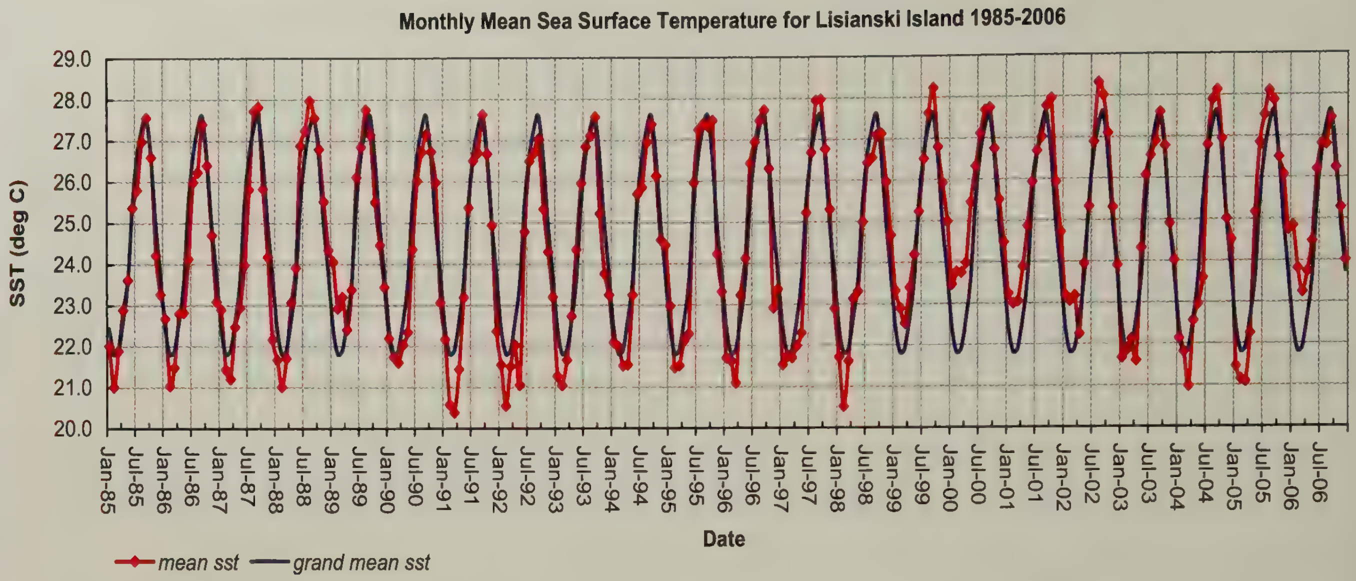
Monthly Mean Sea Surface Temperature for Pearl and Hermes 1985-2006

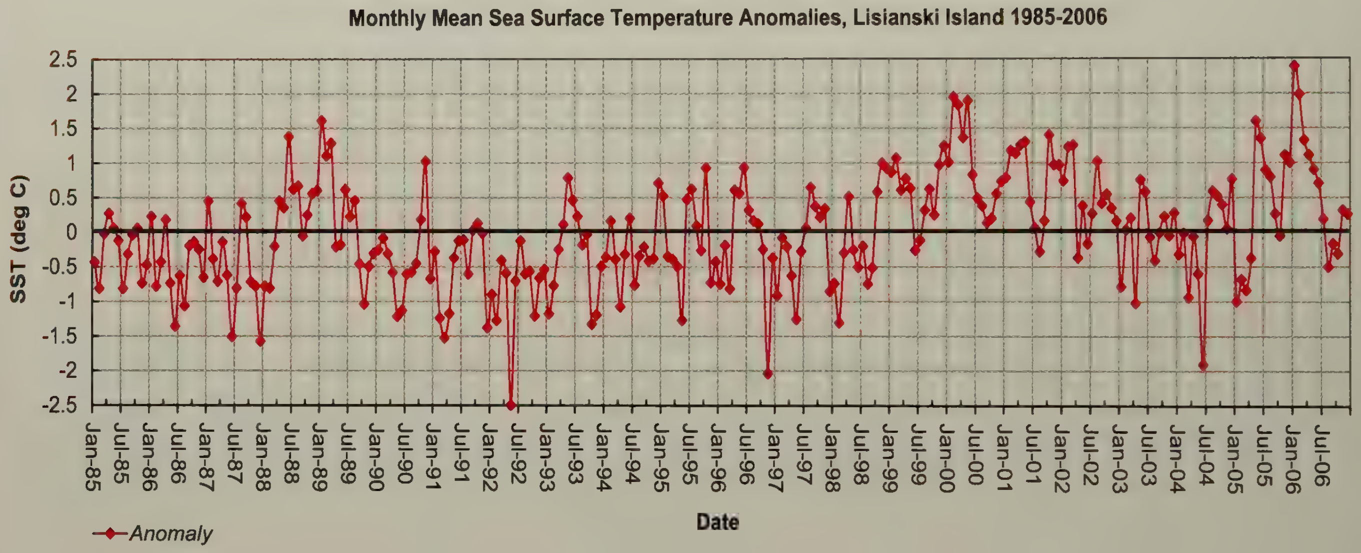


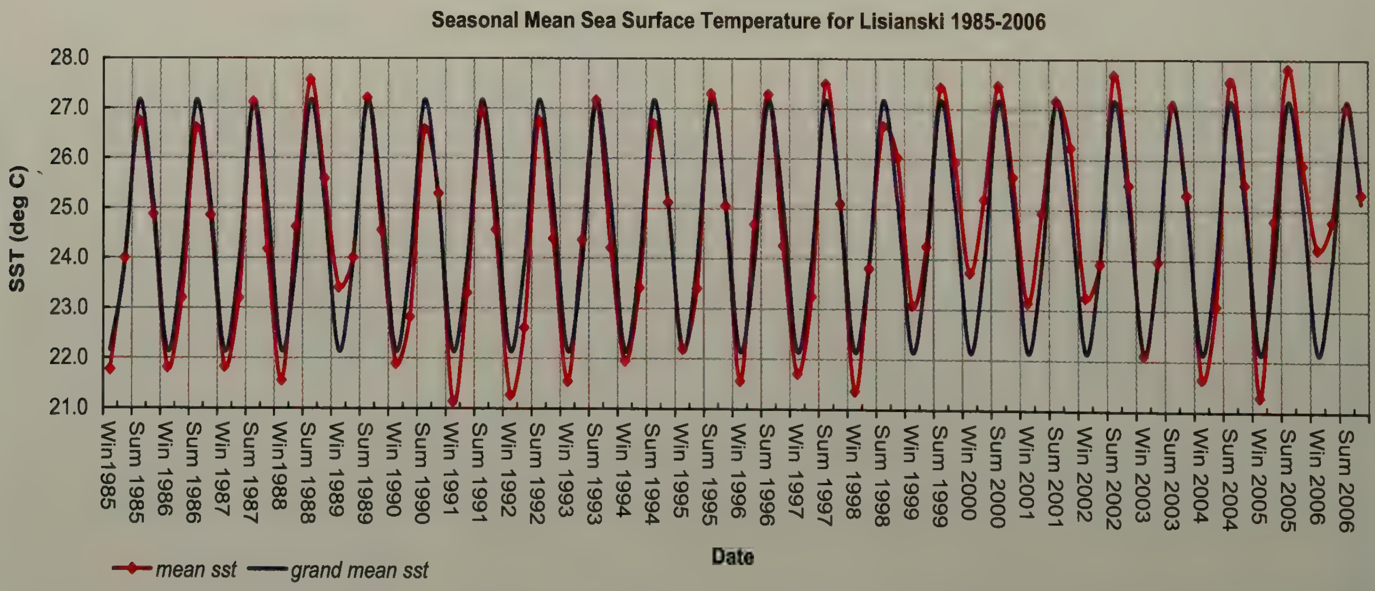
Monthly Mean Sea Surface Temperature Anomalies, Pearl and Hermes 1985-2006



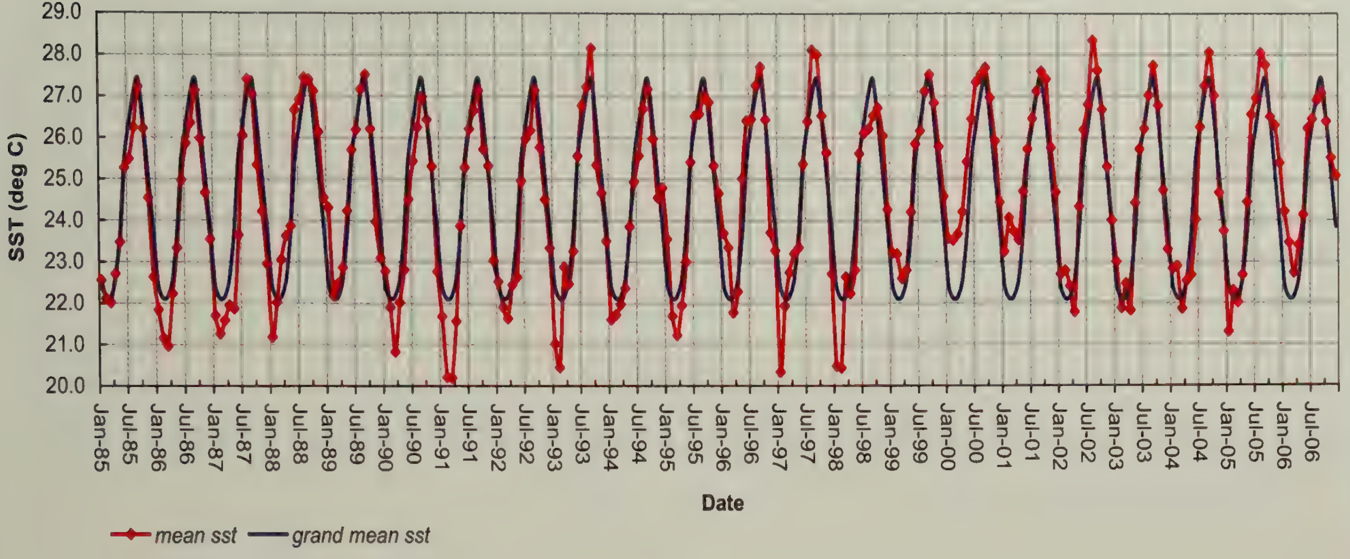
Seasonal Mean Sea Surface Temperature for Pearl and Hermes 1985-2006


Monthly Mean Sea Surface Temperature for Lisianski Island 1985-2006

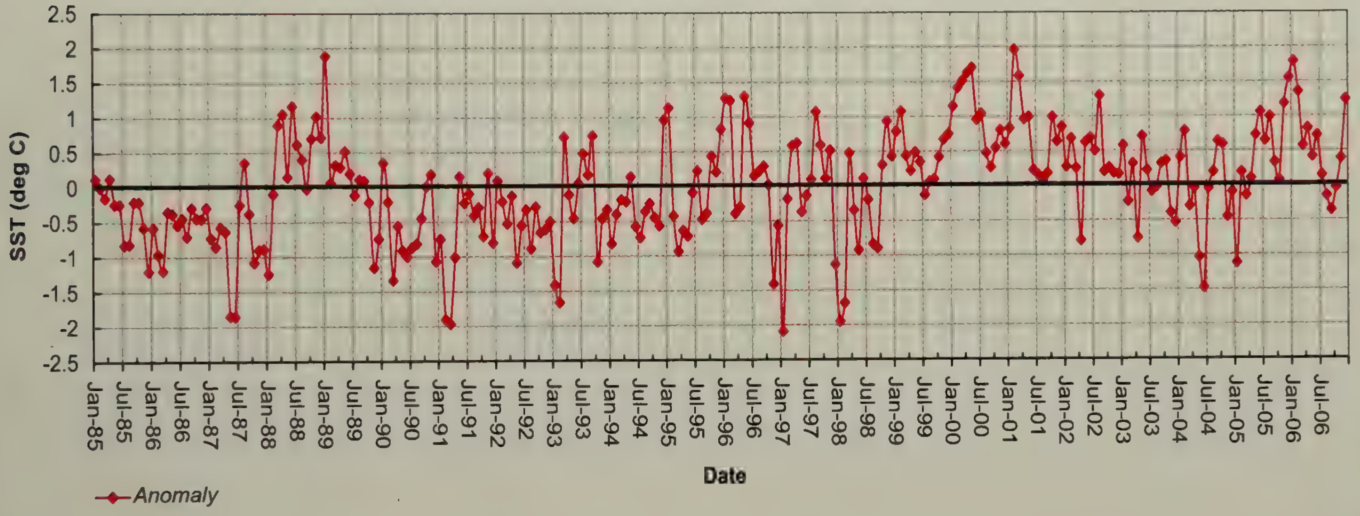

Monthly Mean Sea Surface Temperature Anomalies, Lisianski Island 1985-2006


Seasonal Mean Sea Surface Temperature for Lisianski 1985-2006

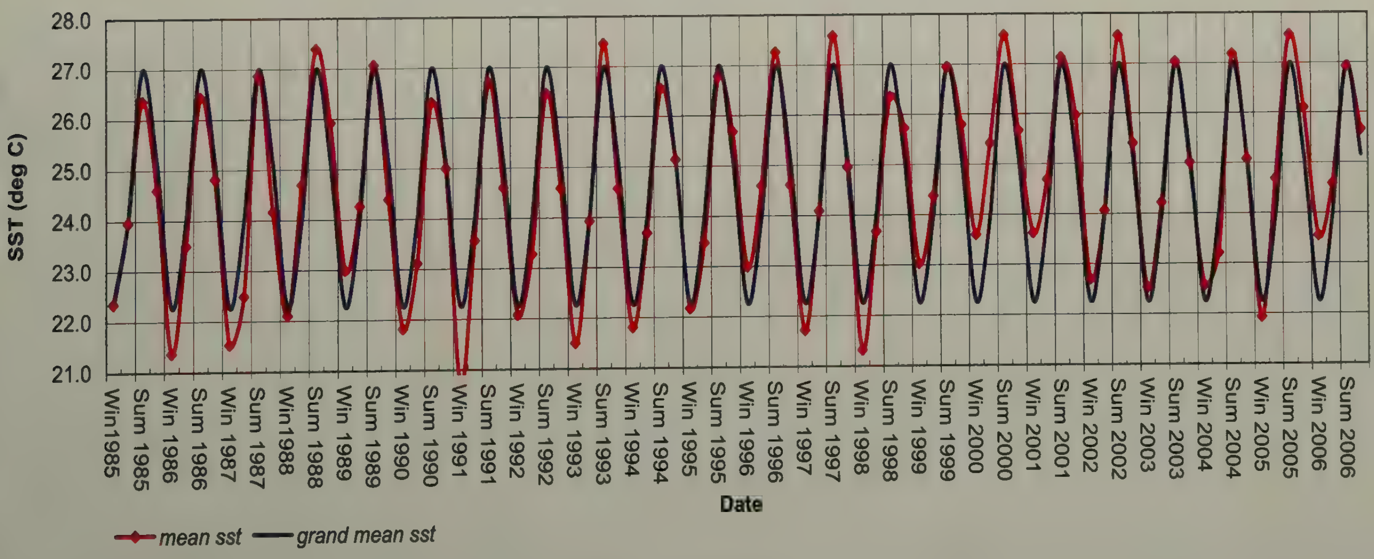
Monthly Mean Sea Surface Temperature for Laysan Island 1985-2006

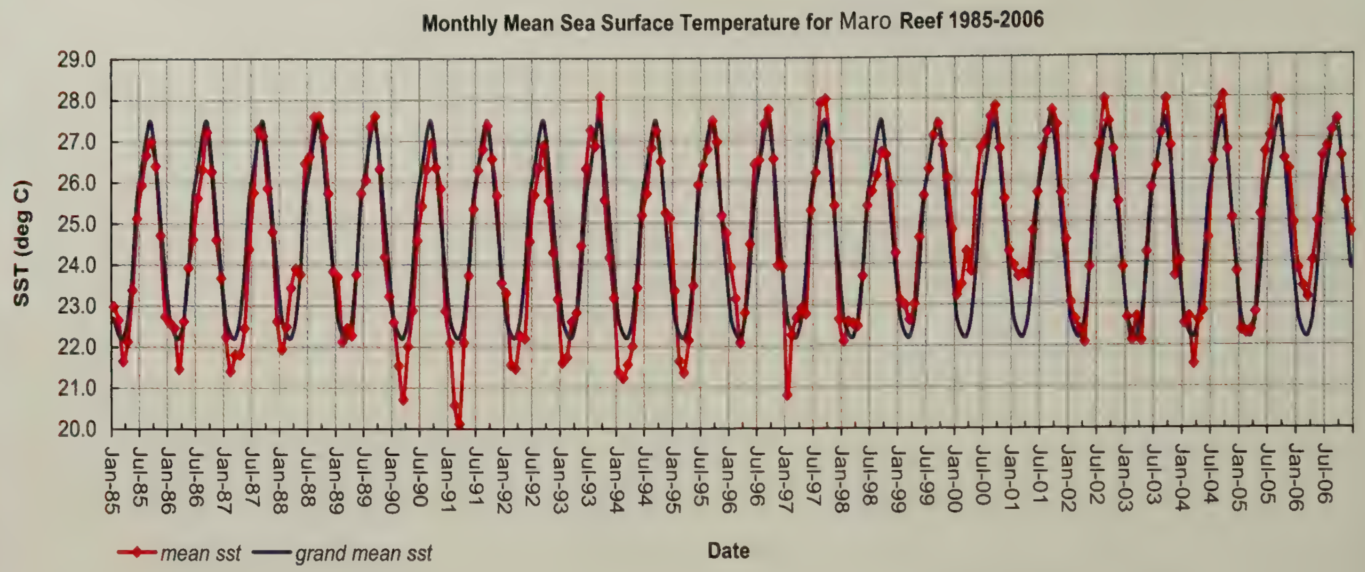


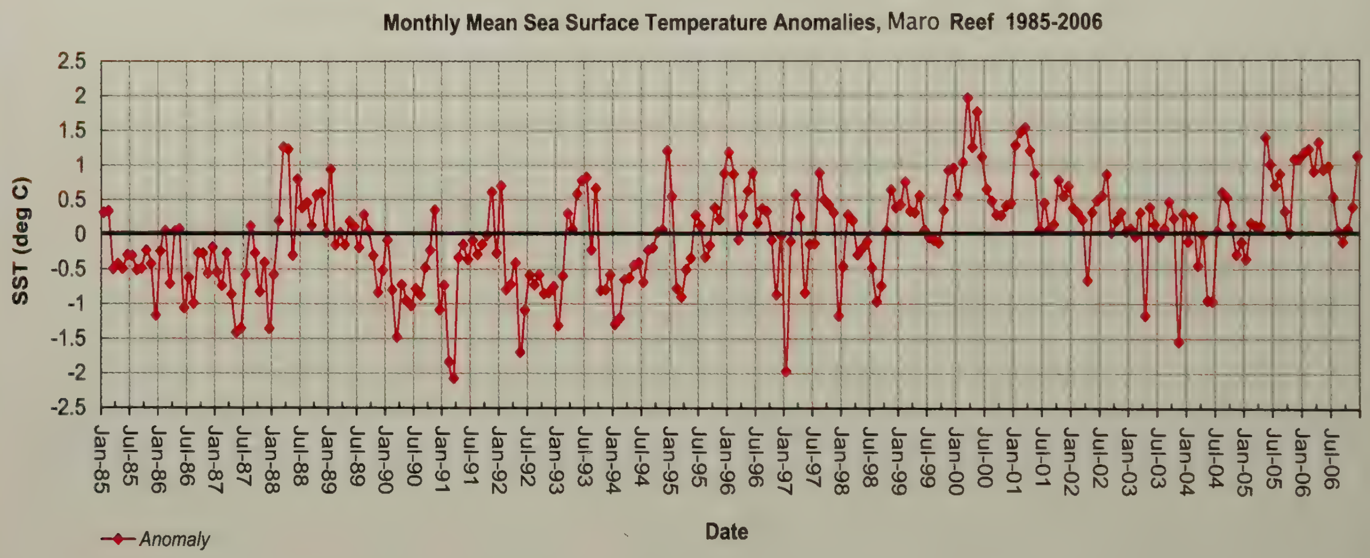
Monthly Mean Sea Surface Temperature Anomalies, Laysan Island 1985-2006

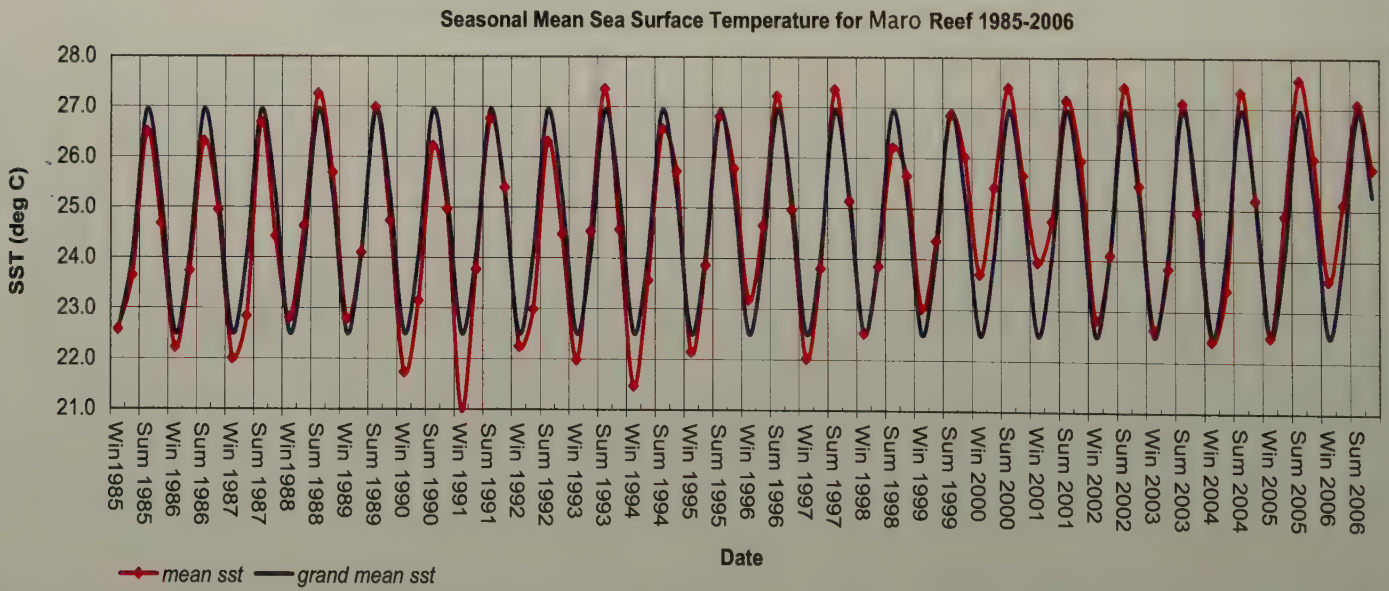


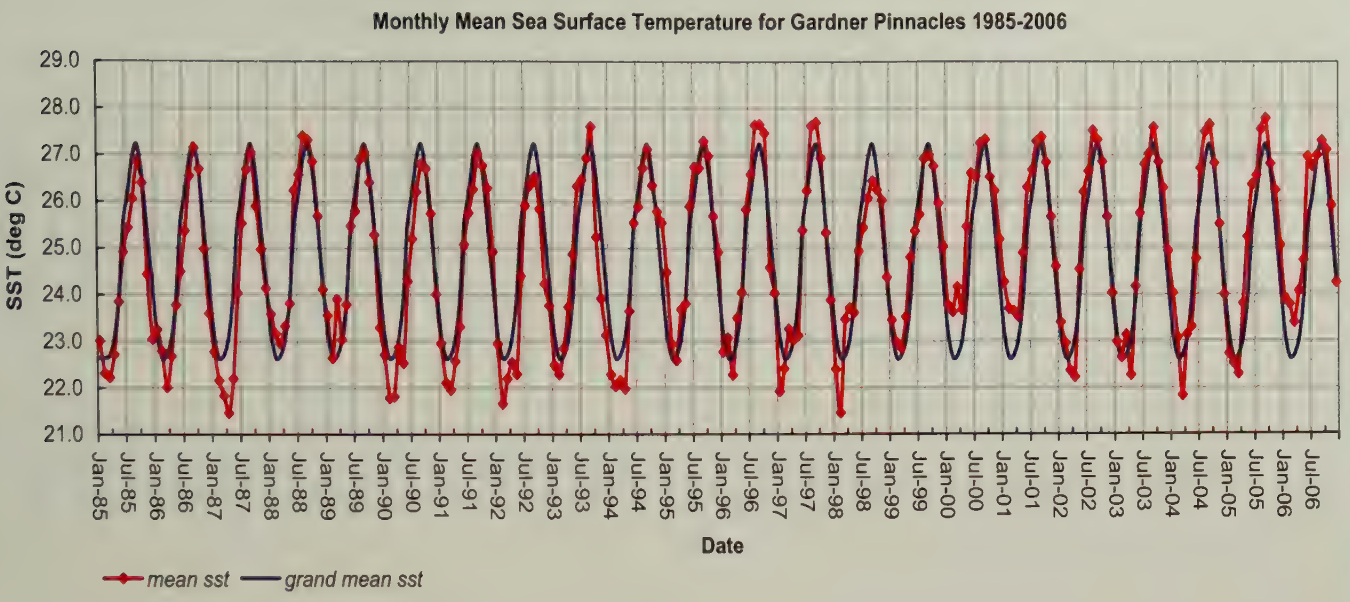
Seasonal Mean Sea Surface Temperature for Laysan Island 1985-2006

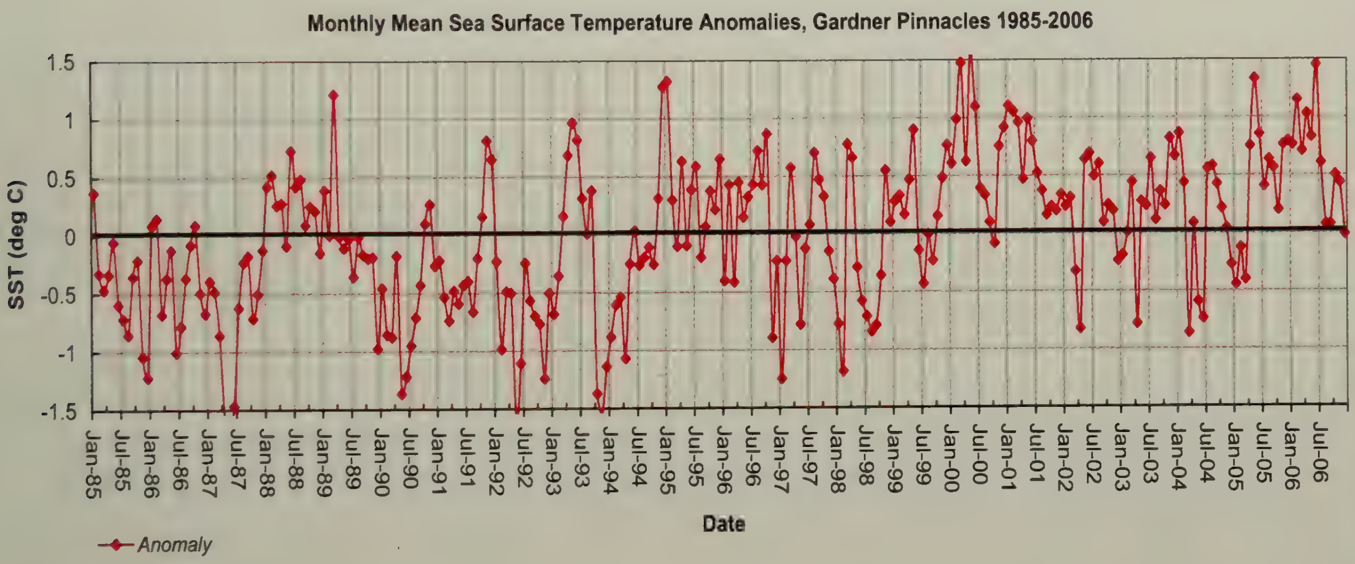


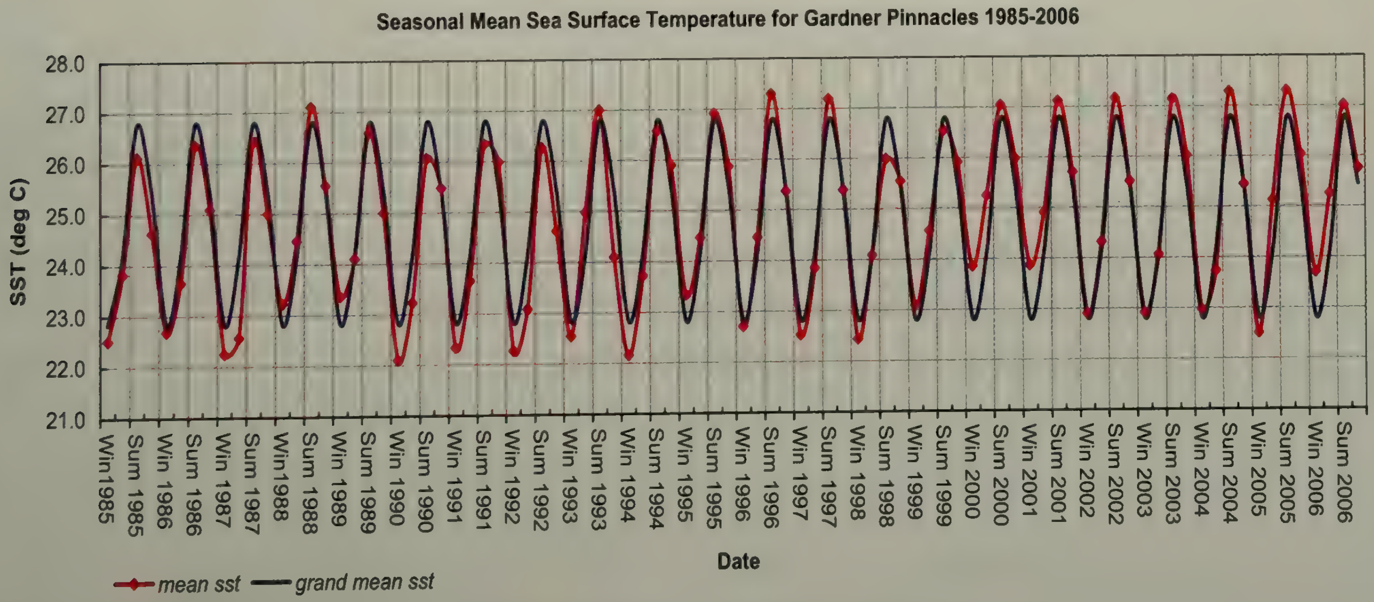

Monthly Mean Sea Surface Temperature for Maro Reef 1985-2006

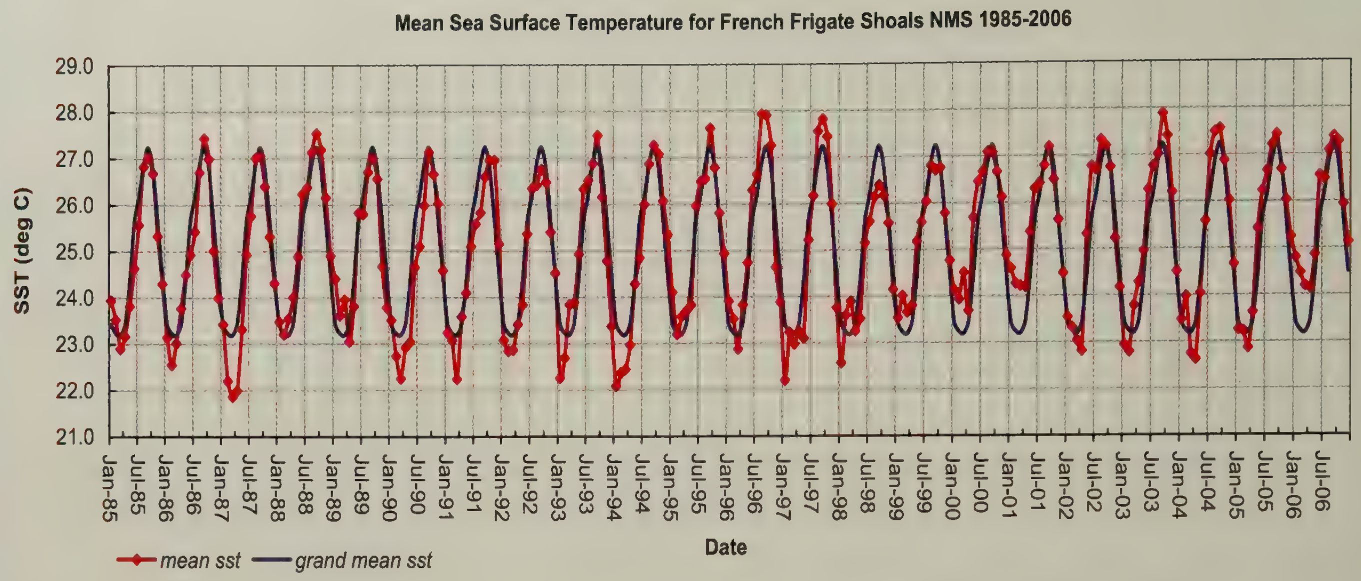

Monthly Mean Sea Surface Temperature Anomalies, Maro Reef 1985-2006


Seasonal Mean Sea Surface Temperature for Maro Reef 1985-2006

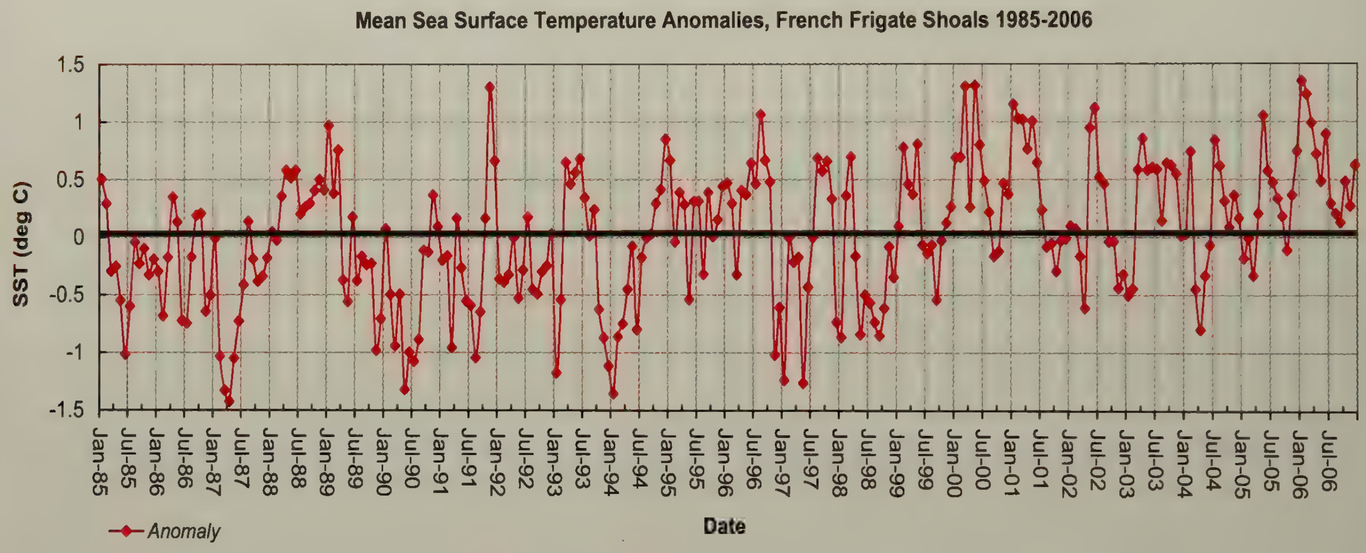

Monthly Mean Sea Surface Temperature for Gardner Pinnacles 1985-2006
SST (deg C)
29.0
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
Jan-85 Jul-85 Jan-86 Jul-86 Jan-87 Jul-87 Jan-88 Jul-88 Jan-89 Jul-89 Jan-90 Jul-90 Jan-91 Jul-91 Jan-92 Jul-92 Jan-93 Jul-93 Jan-94 Jul-94 Jan-95 Jul-95 Jan-96 Jul-96 Jan-97 Jul-97 Jan-98 Jul-98 Jan-99 Jul-99 Jan-00 Jul-00 Jan-01 Jul-01 Jan-02 Jul-02 Jan-03 Jul-03 Jan-04 Jul-04 Jan-05 Jul-05 Jan-06 Jul-06
Date
mean sst
grand mean sst


Monthly Mean Sea Surface Temperature Anomalies, Gardner Pinnacles 1985-2006
SST (deg C)
1.5
1
0.5
0
-0.5
-1
-1.5
Jan-85 Jul-85 Jan-86 Jul-86 Jan-87 Jul-87 Jan-88 Jul-88 Jan-89 Jul-89 Jan-90 Jul-90 Jan-91 Jul-91 Jan-92 Jul-92 Jan-93 Jul-93 Jan-94 Jul-94 Jan-95 Jul-95 Jan-96 Jul-96 Jan-97 Jul-97 Jan-98 Jul-98 Jan-99 Jul-99 Jan-00 Jul-00 Jan-01 Jul-01 Jan-02 Jul-02 Jan-03 Jul-03 Jan-04 Jul-04 Jan-05 Jul-05 Jan-06 Jul-06
Date
Anomaly

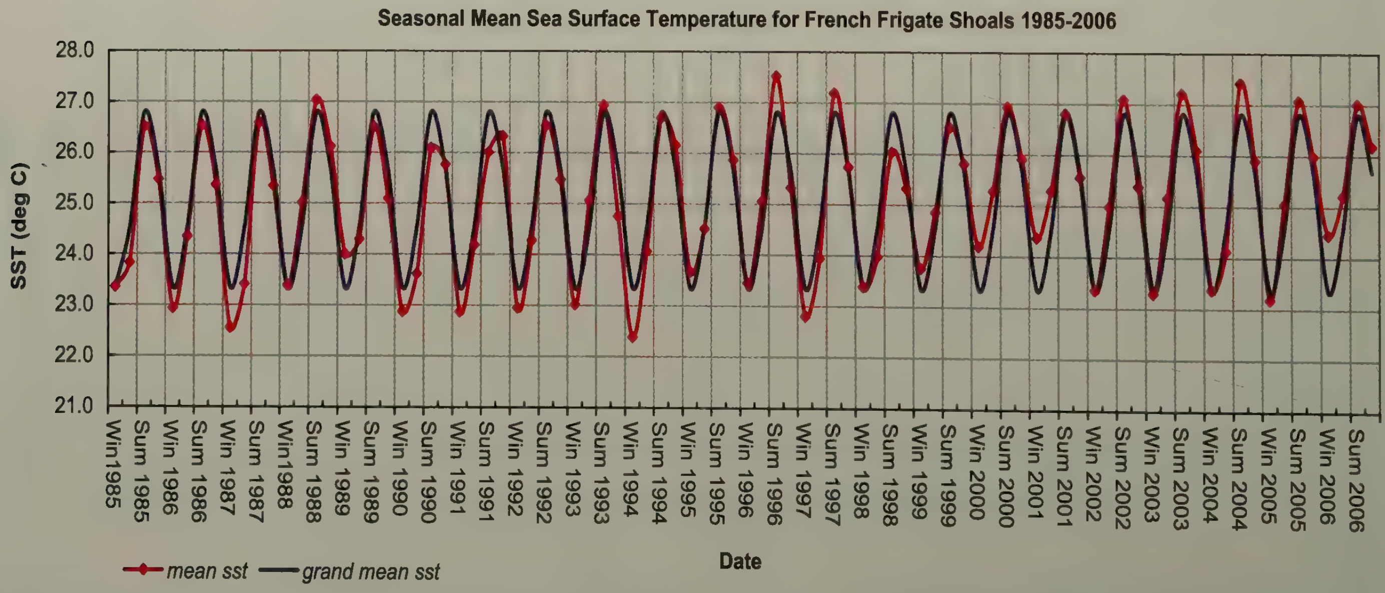

Seasonal Mean Sea Surface Temperature for Gardner Pinnacles 1985-2006
SST (deg C)
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
Win1985 Sum 1985 Win 1986 Sum 1986 Win 1987 Sum 1987 Win1988 Sum 1988 Win 1989 Sum 1989 Win 1990 Sum 1990 Win 1991 Sum 1991 Win 1992 Sum 1992 Win 1993 Sum 1993 Win 1994 Sum 1994 Win 1995 Sum 1995 Win 1996 Sum 1996 Win 1997 Sum 1997 Win 1998 Sum 1998 Win 1999 Sum 1999 Win 2000 Sum 2000 Win 2001 Sum 2001 Win 2002 Sum 2002 Win 2003 Sum 2003 Win 2004 Sum 2004 Win 2005 Sum 2005 Win 2006 Sum 2006
Date
mean sst
grand mean sst



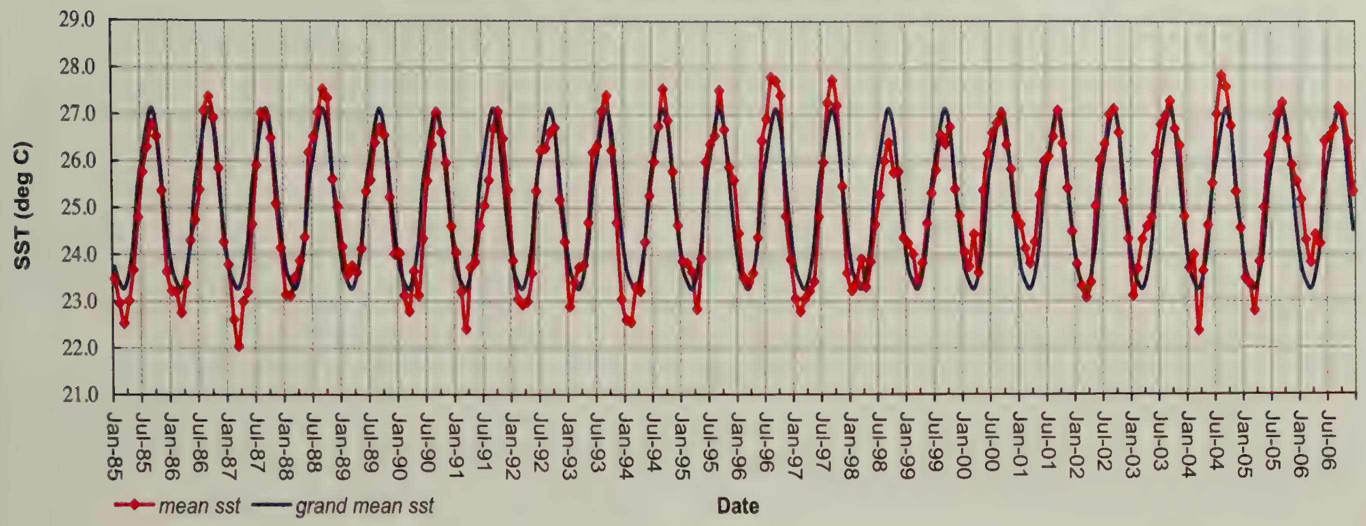
Mean Sea Surface Temperature for French Frigate Shoals NMS 1985-2006



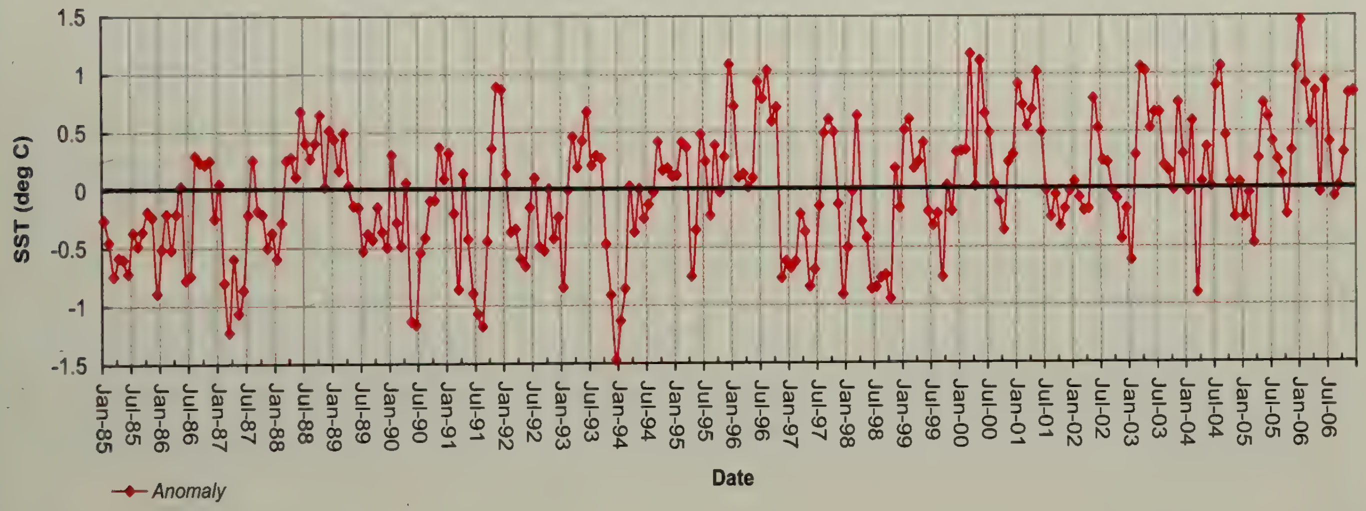
Mean Sea Surface Temperature Anomalies, French Frigate Shoals 1985-2006



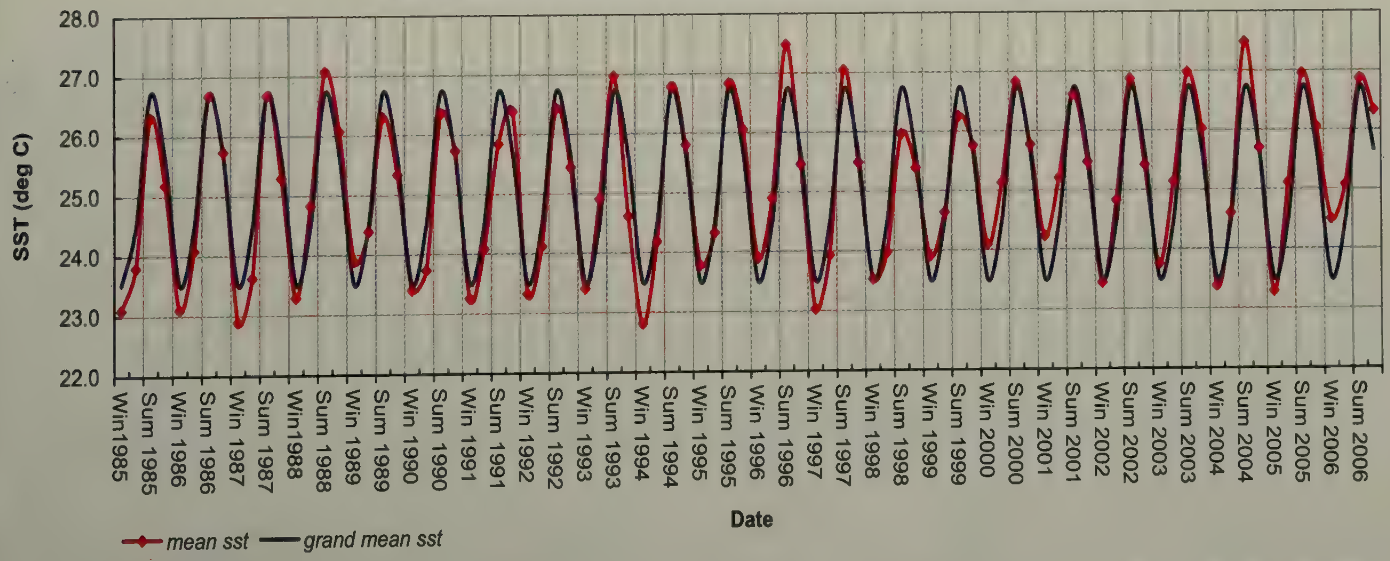
Seasonal Mean Sea Surface Temperature for French Frigate Shoals 1985-2006



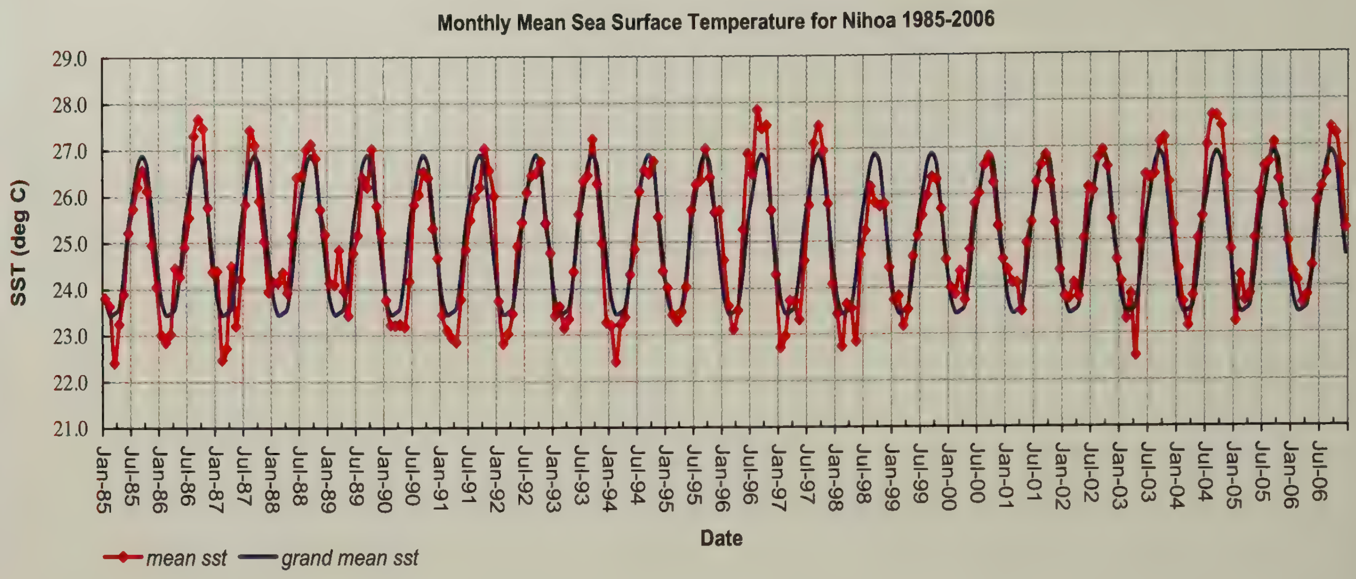
Monthly Mean Sea Surface Temperature for Mokumanamana Island 1985-2006

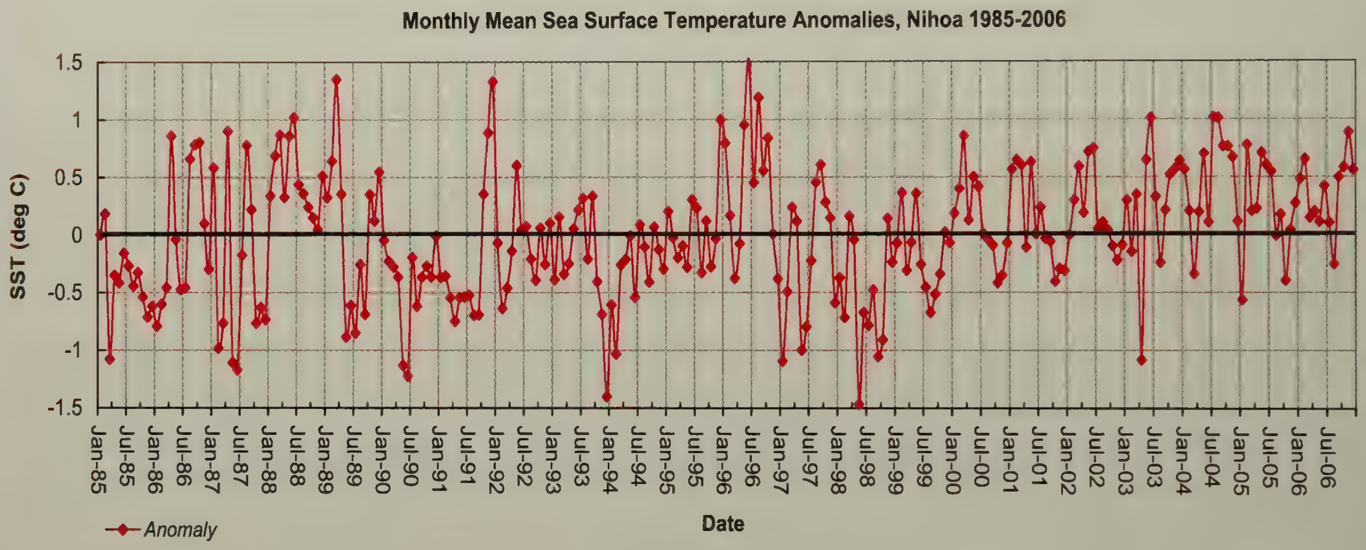


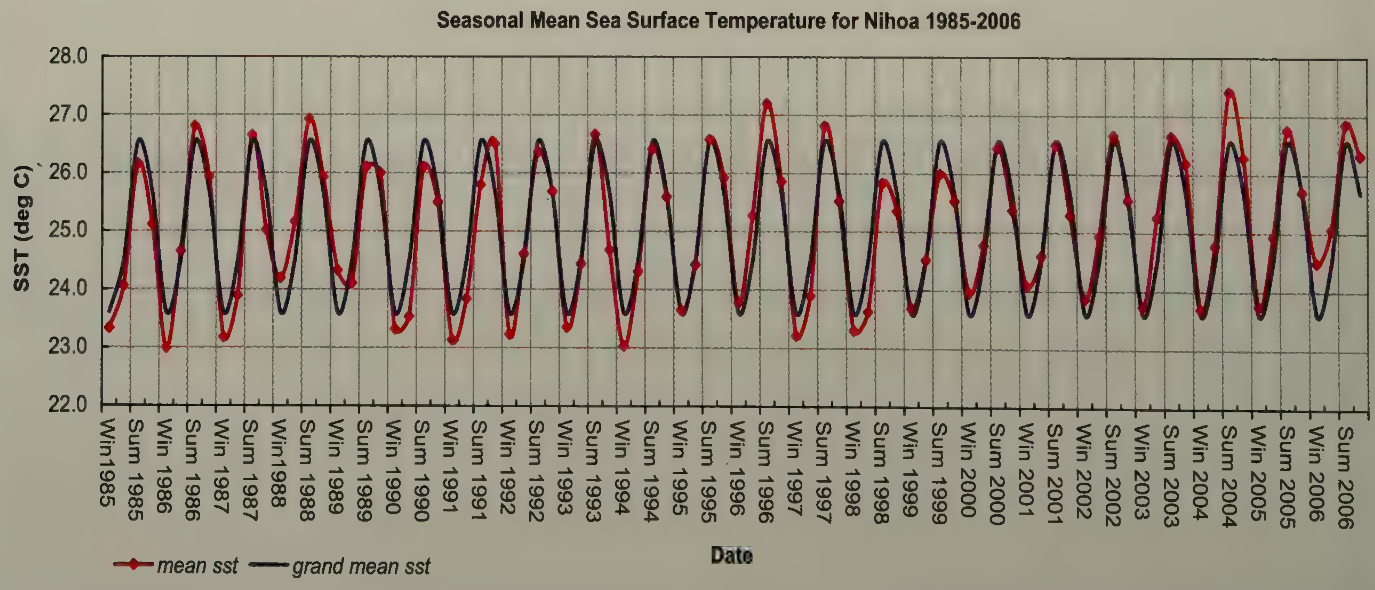
Monthly Mean Sea Surface Temperature Anomalies, Mokumanamana Island 1985-2006



Seasonal Mean Sea Surface Temperature for Mokumanamana Island 1985-2006

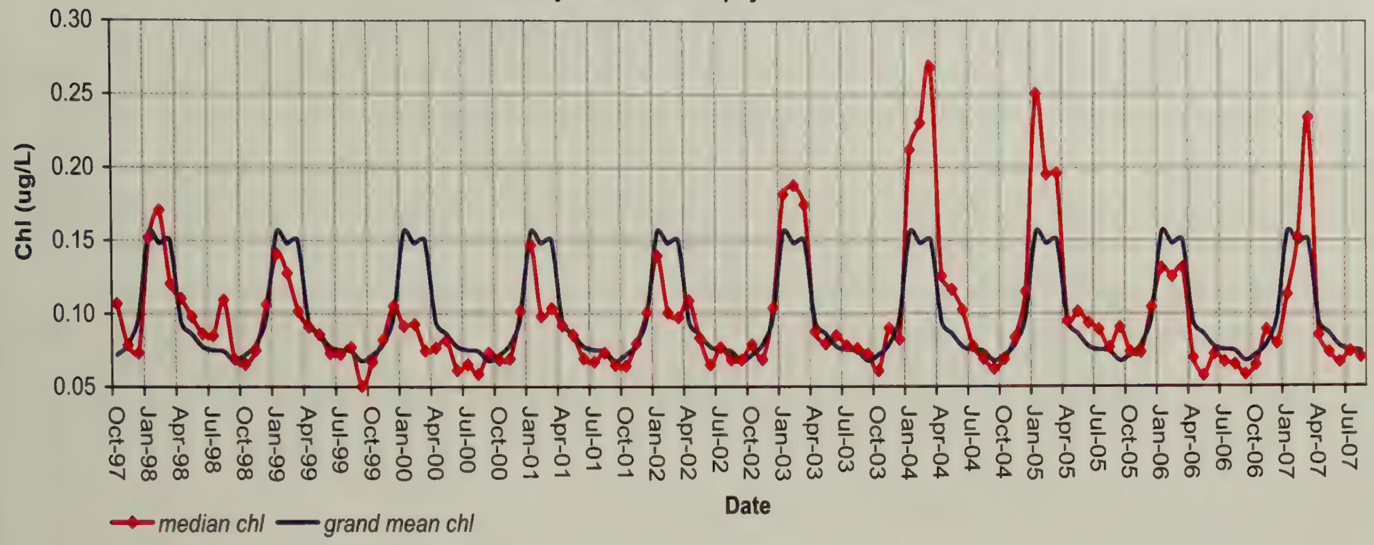

Monthly Mean Sea Surface Temperature for Nihoa 1985-2006
SST (deg C)
29.0
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
Jan-85
Jul-85
Jan-86
Jul-86
Jan-87
Jul-87
Jan-88
Jul-88
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
Jan-00
Jul-00
Jan-01
Jul-01
Jan-02
Jul-02
Jan-03
Jul-03
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Date
mean sst
grand mean sst


Monthly Mean Sea Surface Temperature Anomalies, Nihoa 1985-2006
SST (deg C)
1.5
1
0.5
0
-0.5
-1
-1.5
Jan-85
Jul-85
Jan-86
Jul-86
Jan-87
Jul-87
Jan-88
Jul-88
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
Jan-00
Jul-00
Jan-01
Jul-01
Jan-02
Jul-02
Jan-03
Jul-03
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Date
Anomaly

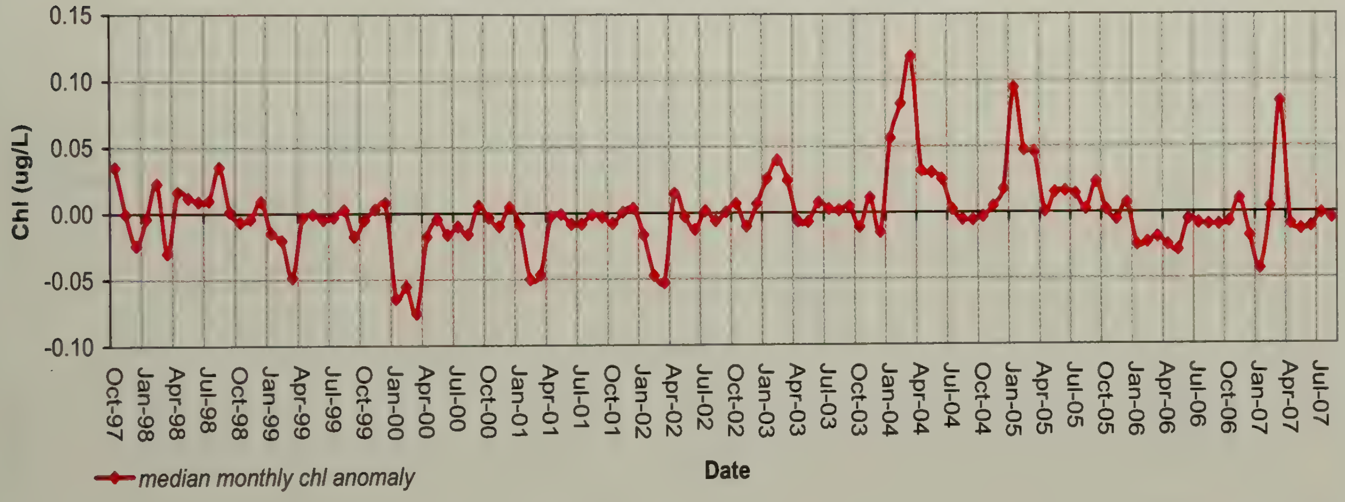

Seasonal Mean Sea Surface Temperature for Nihoa 1985-2006
SST (deg C)
28.0
27.0
26.0
25.0
24.0
23.0
22.0
Win1985
Sum 1985
Win 1986
Sum 1986
Win 1987
Sum 1987
Win1988
Sum 1988
Win 1989
Sum 1989
Win 1990
Sum 1990
Win 1991
Sum 1991
Win 1992
Sum 1992
Win 1993
Sum 1993
Win 1994
Sum 1994
Win 1995
Sum 1995
Win 1996
Sum 1996
Win 1997
Sum 1997
Win 1998
Sum 1998
Win 1999
Sum 1999
Win 2000
Sum 2000
Win 2001
Sum 2001
Win 2002
Sum 2002
Win 2003
Sum 2003
Win 2004
Sum 2004
Win 2005
Sum 2005
Win 2006
Sum 2006
Date
mean sst
grand mean sst

APPENDIX II. CHLOROPHYLL (AND RELATED) TIME SERIES PLOTS

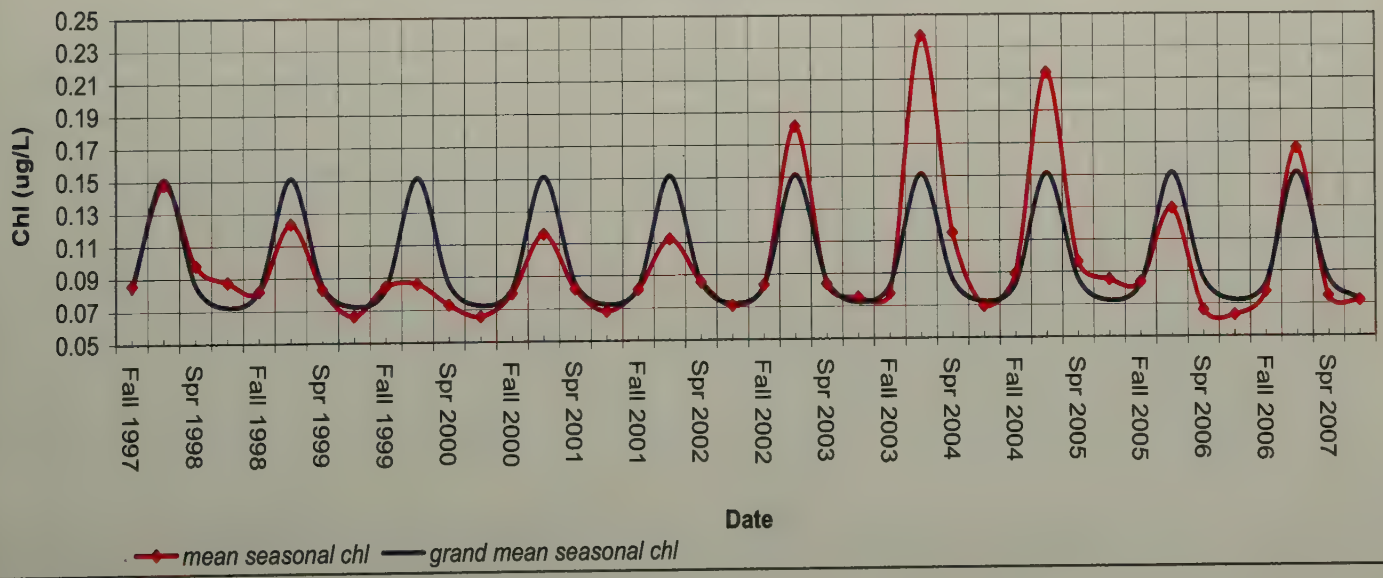
Monthly Median Chlorophyll for Kure 1997-2007

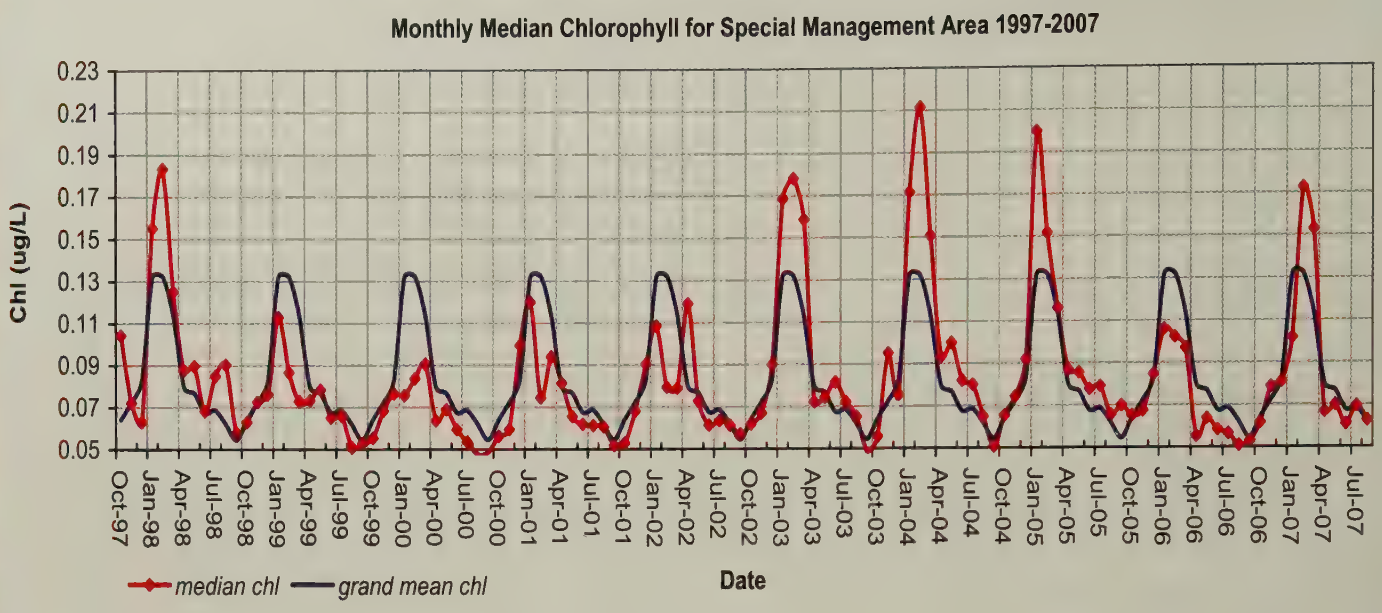


Monthly Median Chlorophyll Anomaly, Kure 1997-2007

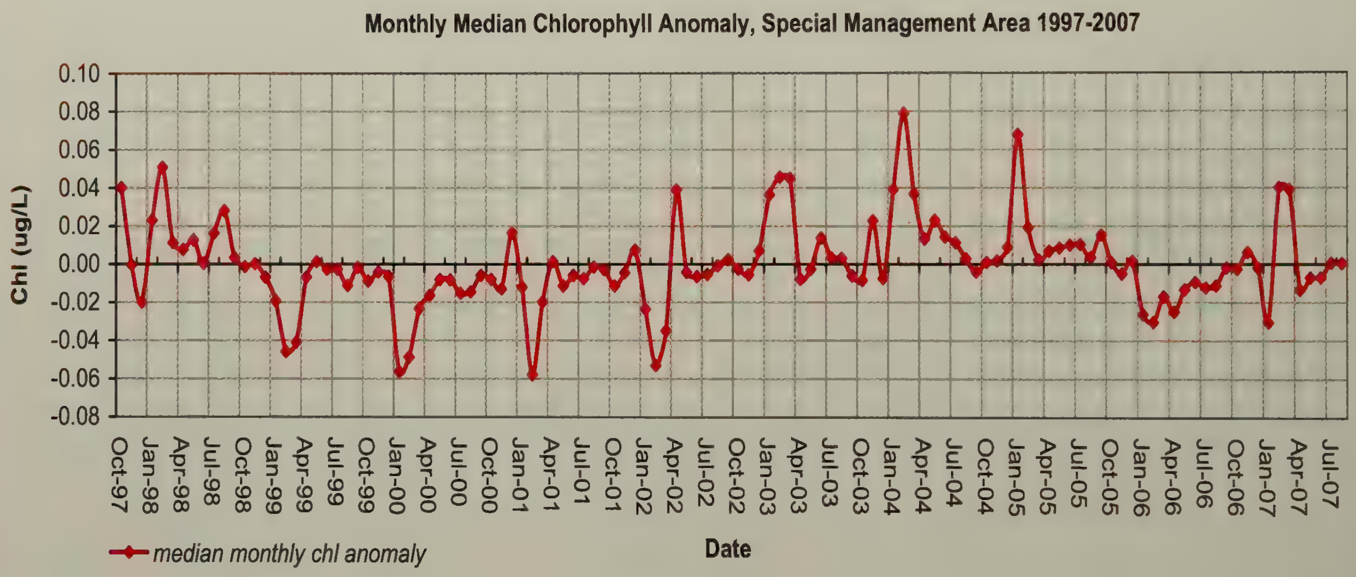


Mean Seasonal Chlorophyll for Kure 1997-2007

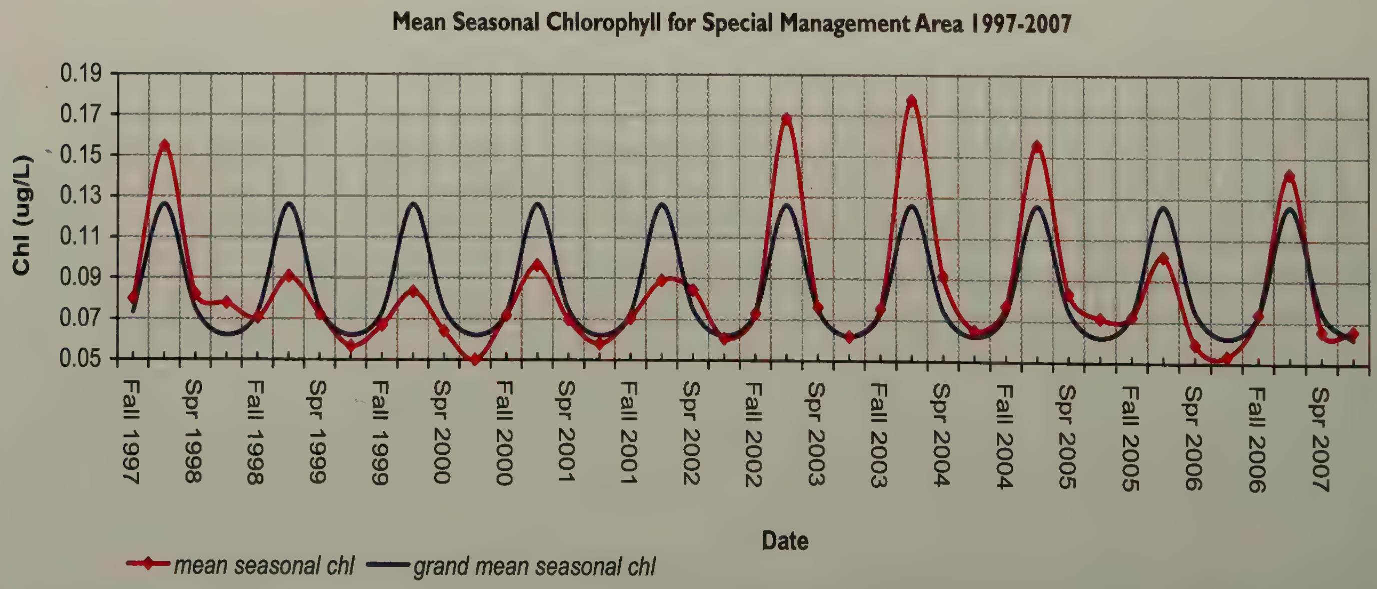




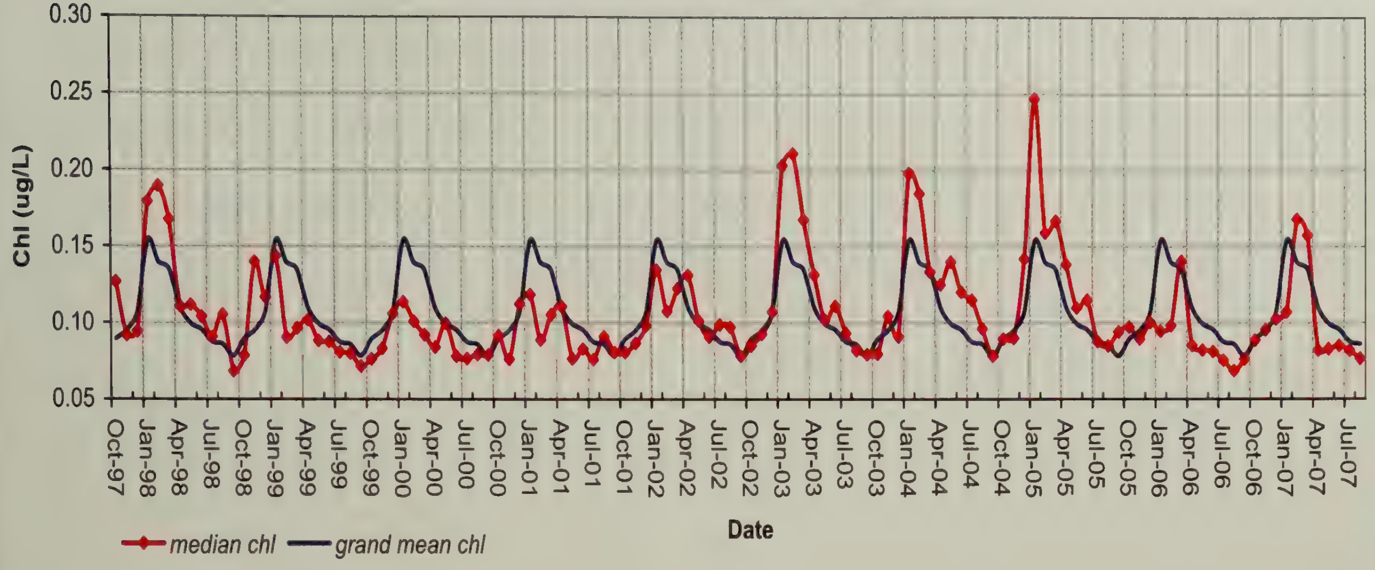
Monthly Median Chlorophyll for Special Management Area 1997-2007



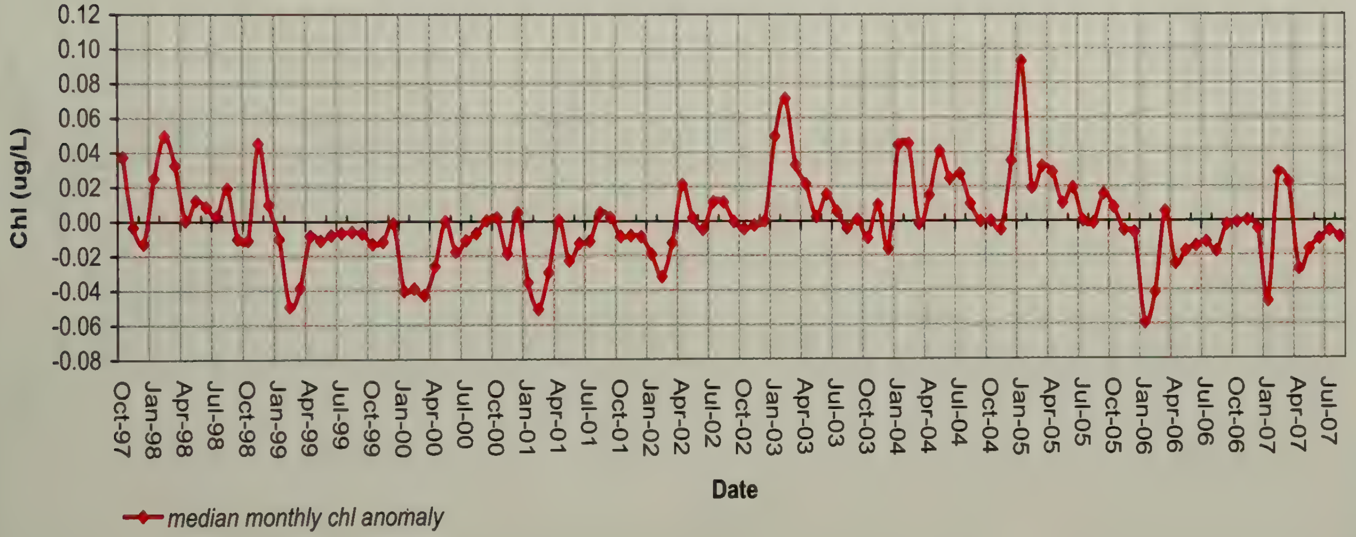
Monthly Median Chlorophyll Anomaly, Special Management Area 1997-2007



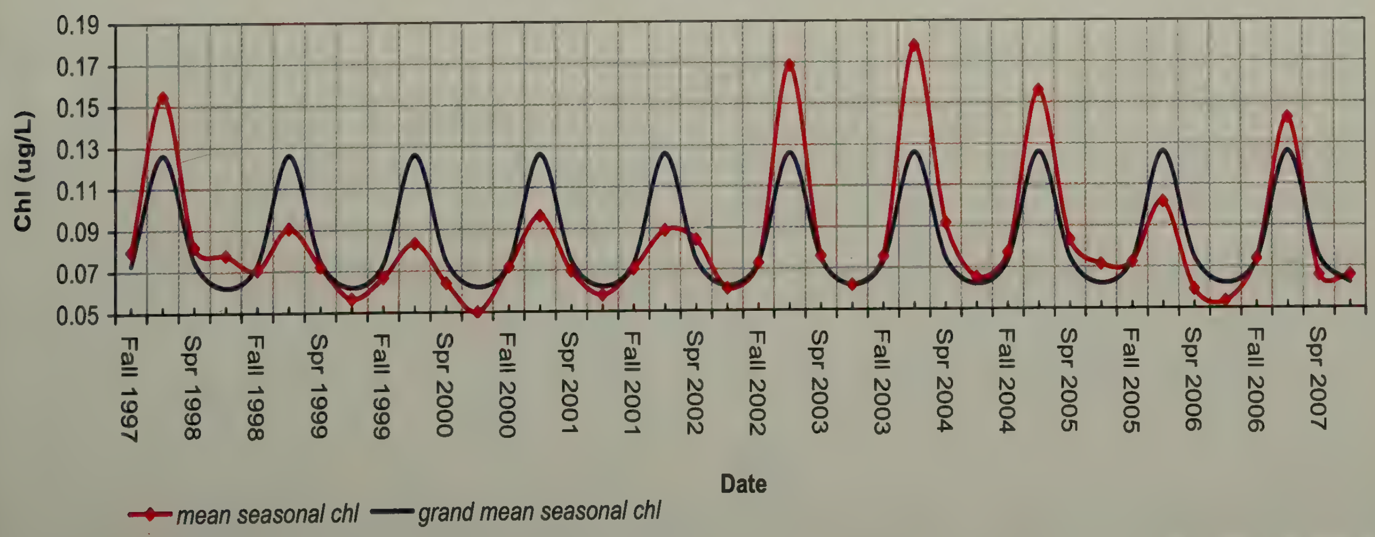
Mean Seasonal Chlorophyll for Special Management Area 1997-2007



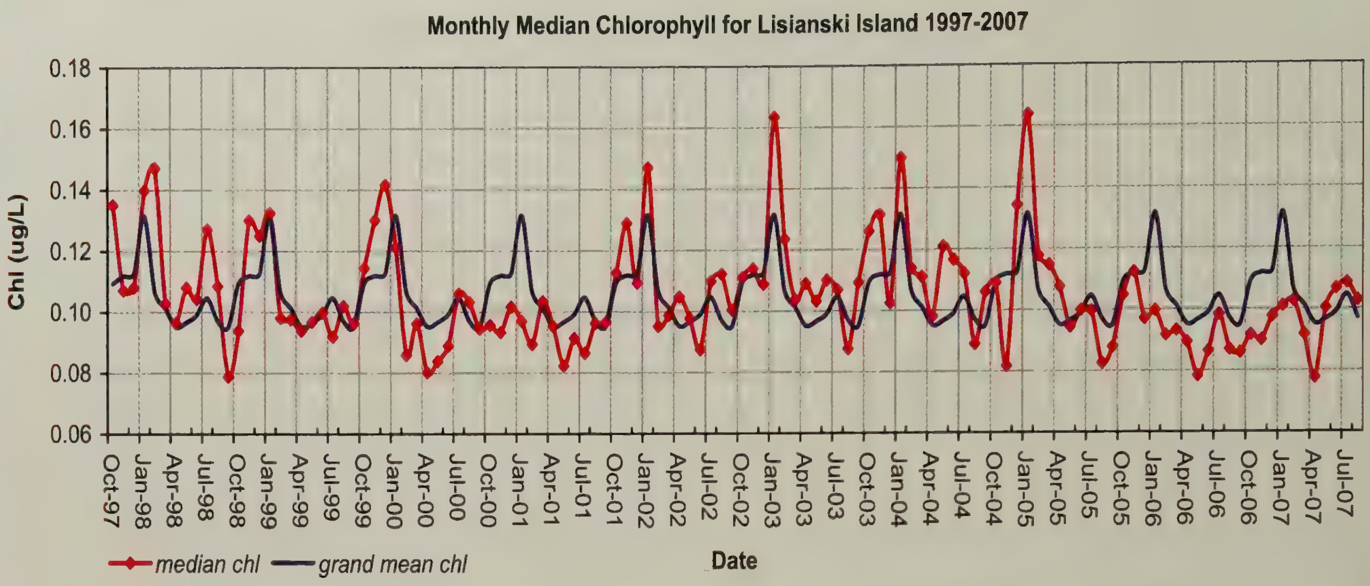
Monthly Median Chlorophyll for Pearl and Hermes 1997-2007



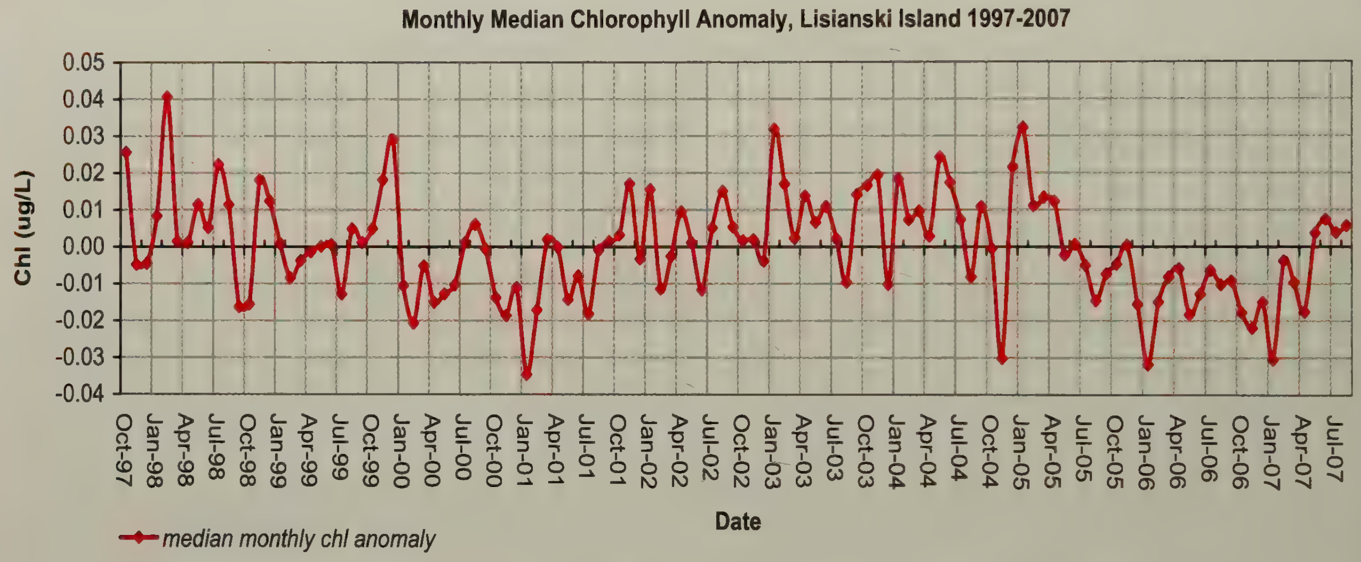
Monthly Median Chlorophyll Anomaly, Pearl and Hermes 1997-2007



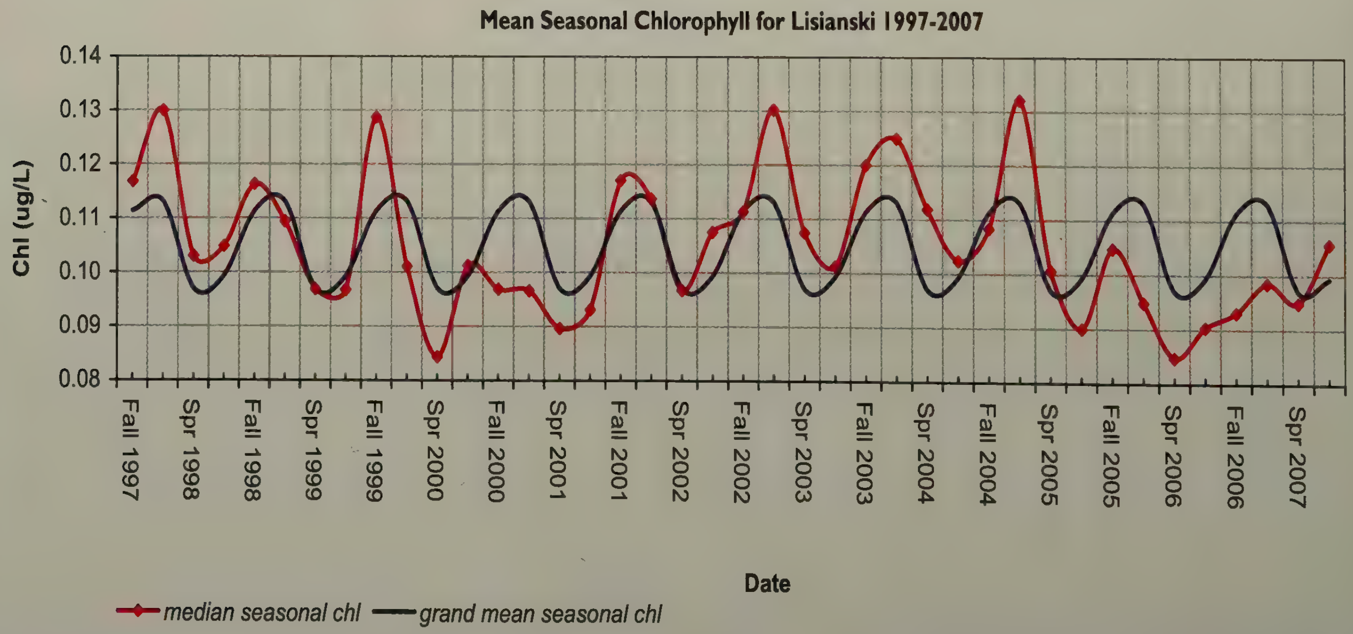
Mean Seasonal Chlorophyll for Pearl and Hermes 1997-2007



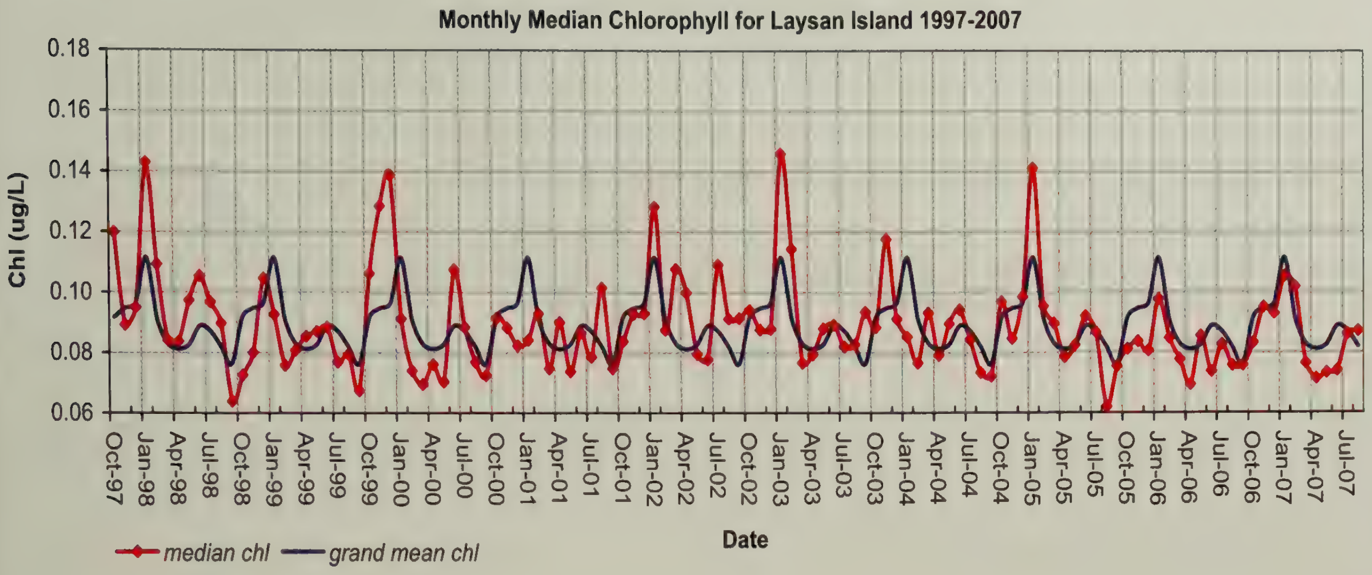
Monthly Median Chlorophyll for Lisianski Island 1997-2007

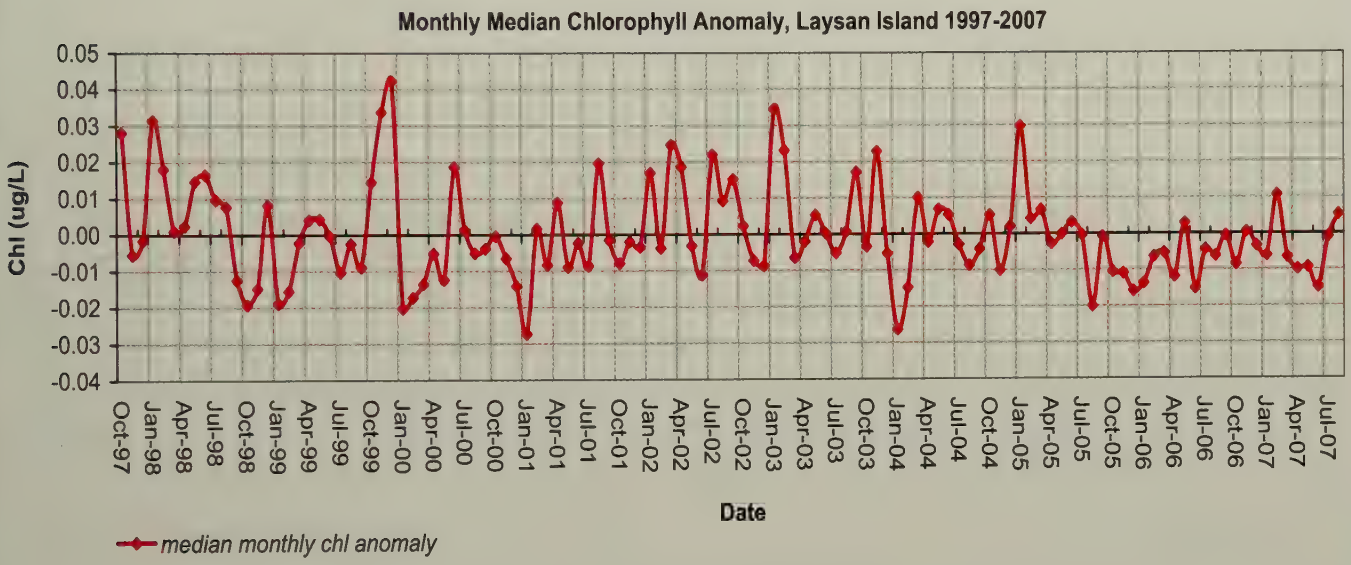


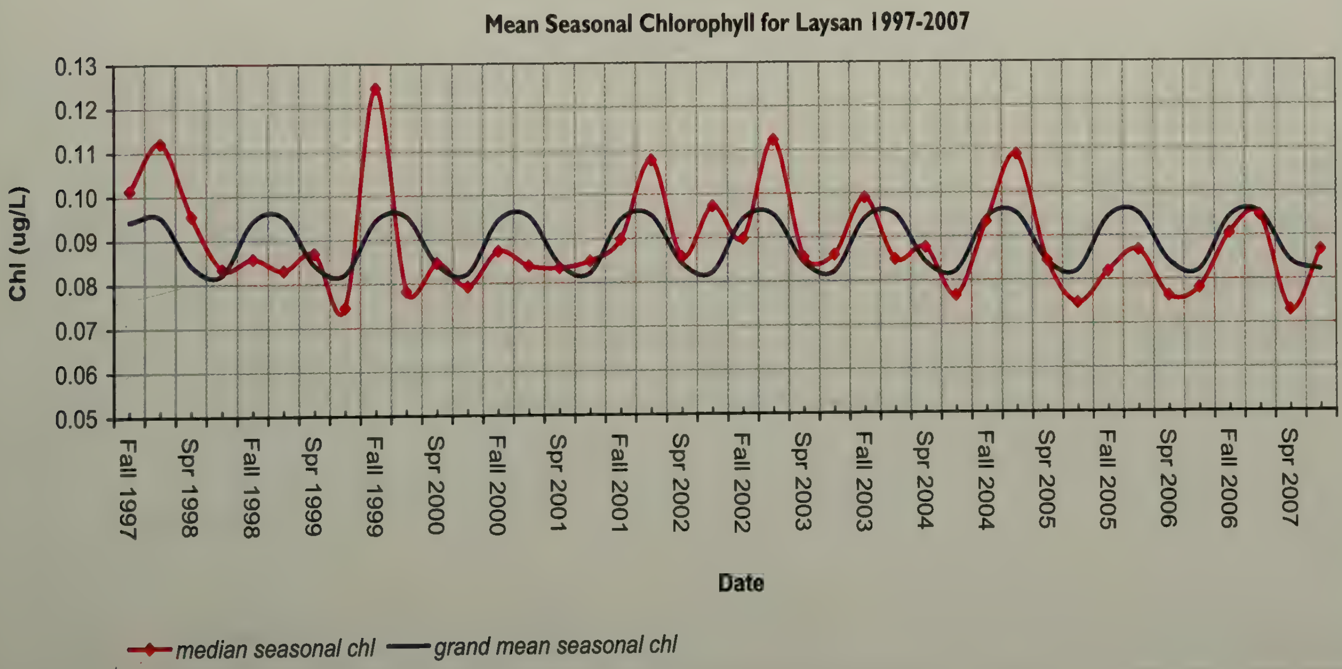
Monthly Median Chlorophyll Anomaly, Lisianski Island 1997-2007

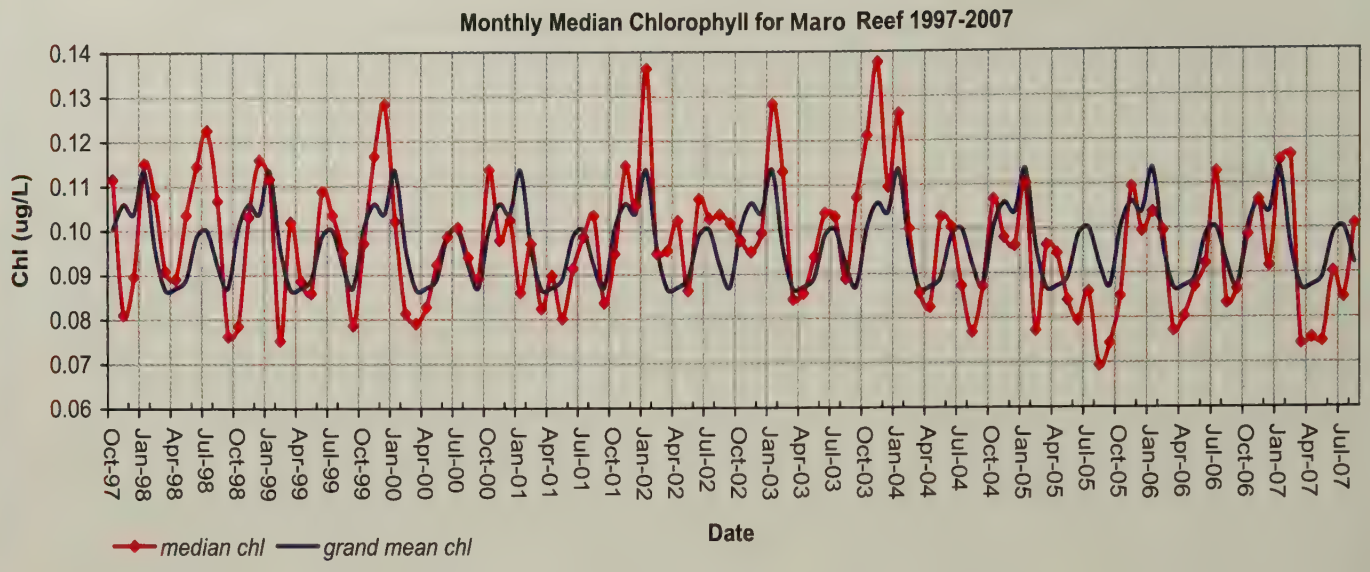


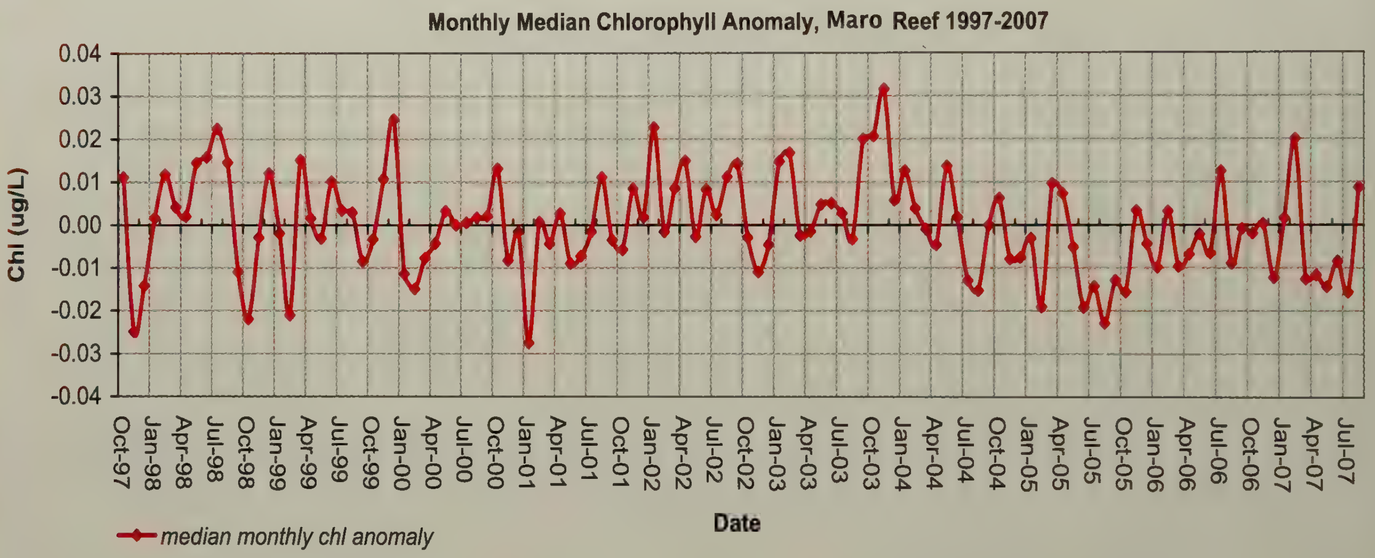
Mean Seasonal Chlorophyll for Lisianski 1997-2007

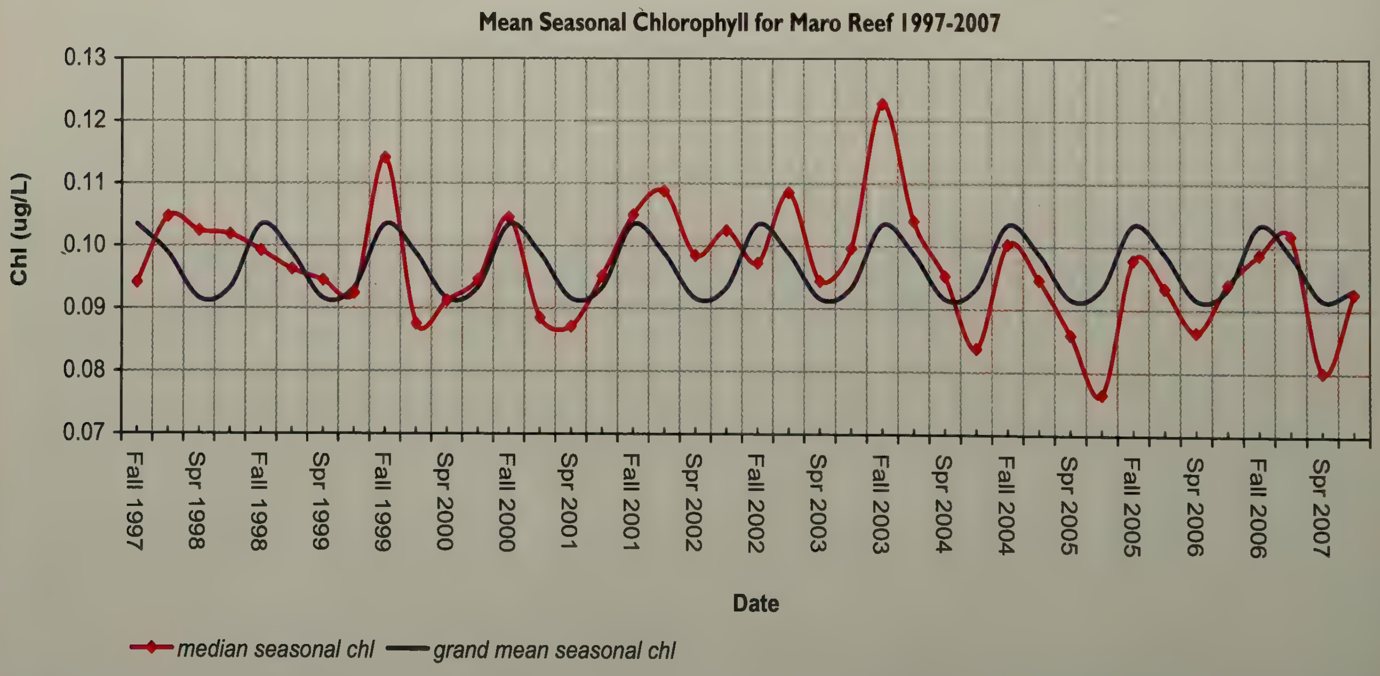

Monthly Median Chlorophyll for Laysan Island 1997-2007
Chl (ug/L)
0.18
0.16
0.14
0.12
0.10
0.08
0.06
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Oct-06
Jan-07
Apr-07
Jul-07
Date
median chl
grand mean chl

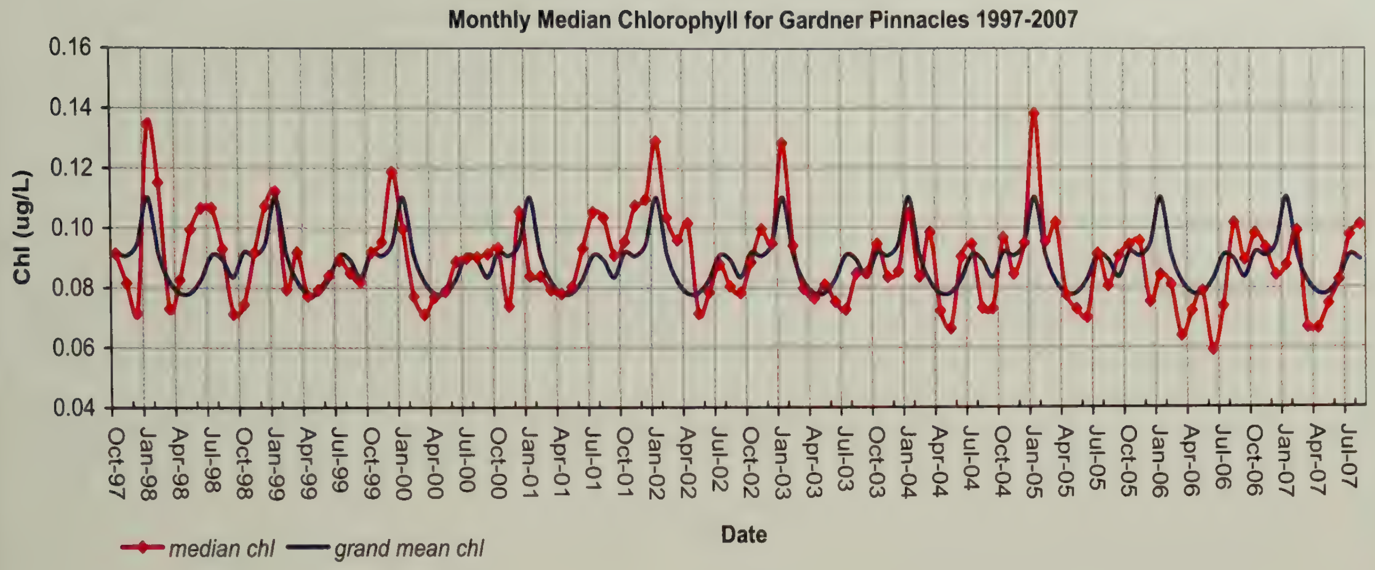

Monthly Median Chlorophyll Anomaly, Laysan Island 1997-2007
Chl (ug/L)
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Oct-06
Jan-07
Apr-07
Jul-07
Date
median monthly chl anomaly

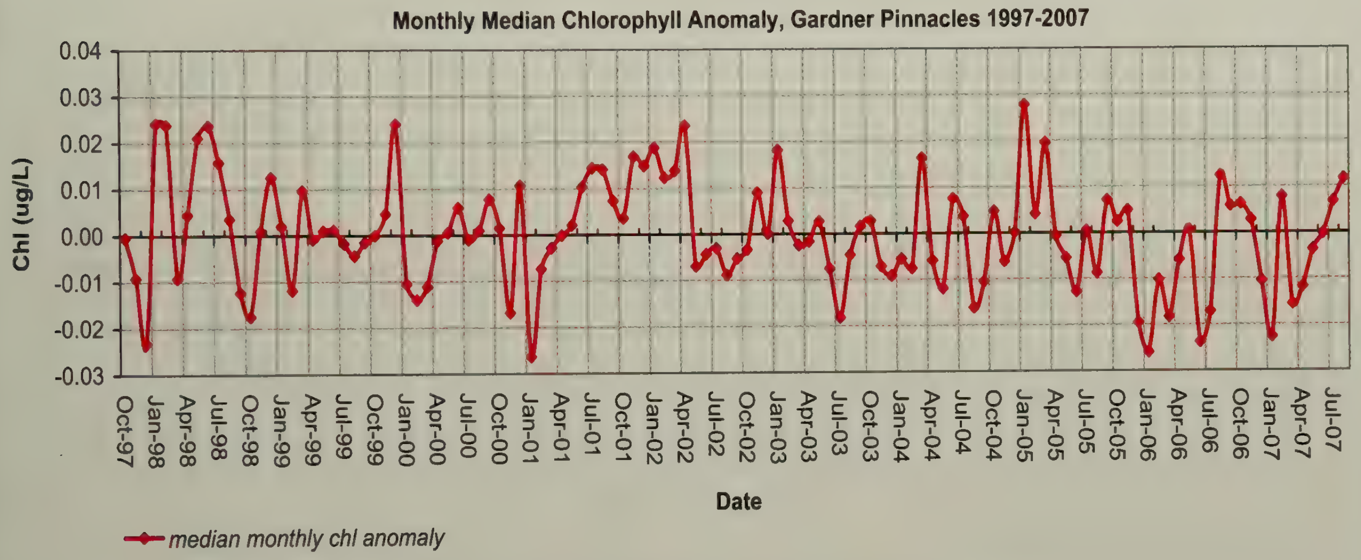

Mean Seasonal Chlorophyll for Laysan 1997-2007
Chl (ug/L)
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
Fall 1997
Spr 1998
Fall 1998
Spr 1999
Fall 1999
Spr 2000
Fall 2000
Spr 2001
Fall 2001
Spr 2002
Fall 2002
Spr 2003
Fall 2003
Spr 2004
Fall 2004
Spr 2005
Fall 2005
Spr 2006
Fall 2006
Spr 2007
Date
median seasonal chl
grand mean seasonal chl

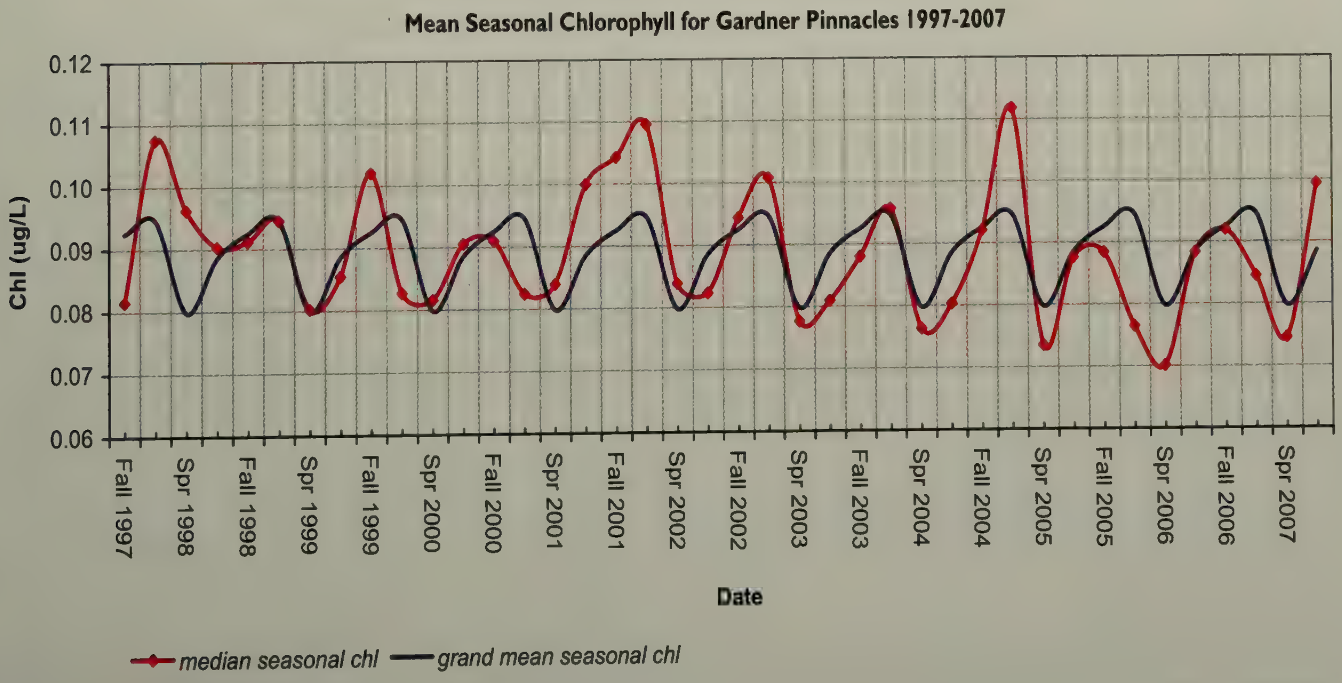

Monthly Median Chlorophyll for Maro Reef 1997-2007


Monthly Median Chlorophyll Anomaly, Maro Reef 1997-2007

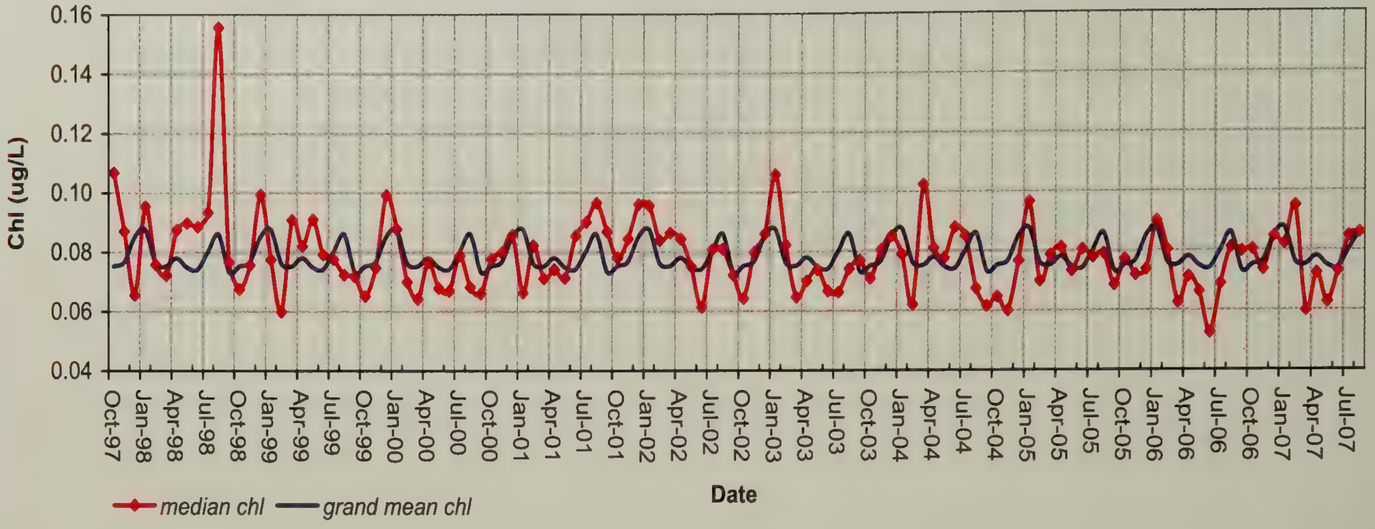

Mean Seasonal Chlorophyll for Maro Reef 1997-2007


Monthly Median Chlorophyll for Gardner Pinnacles 1997-2007

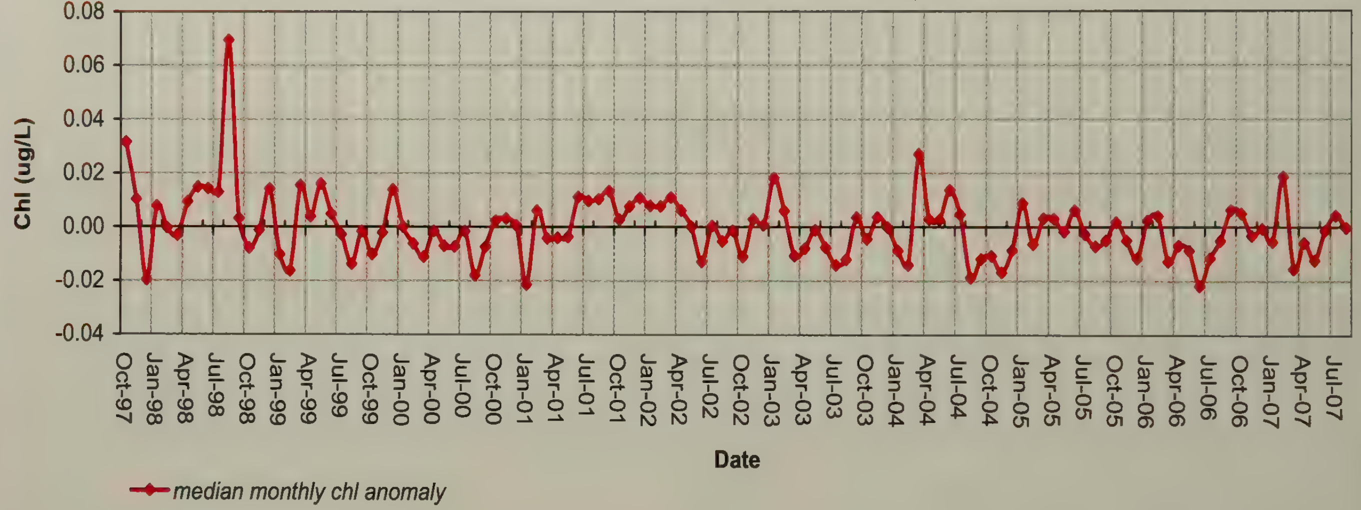

Monthly Median Chlorophyll Anomaly, Gardner Pinnacles 1997-2007


Mean Seasonal Chlorophyll for Gardner Pinnacles 1997-2007

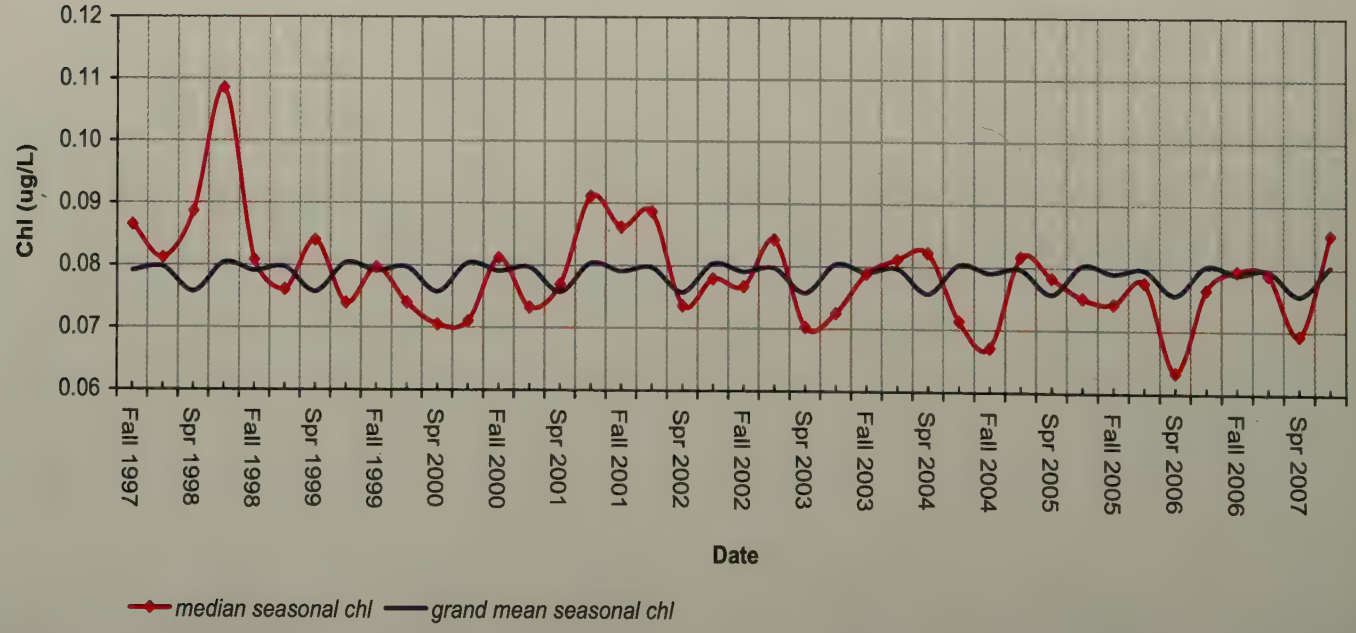
Monthly Median Chlorophyll for French Frigate Shoals 1997-2007

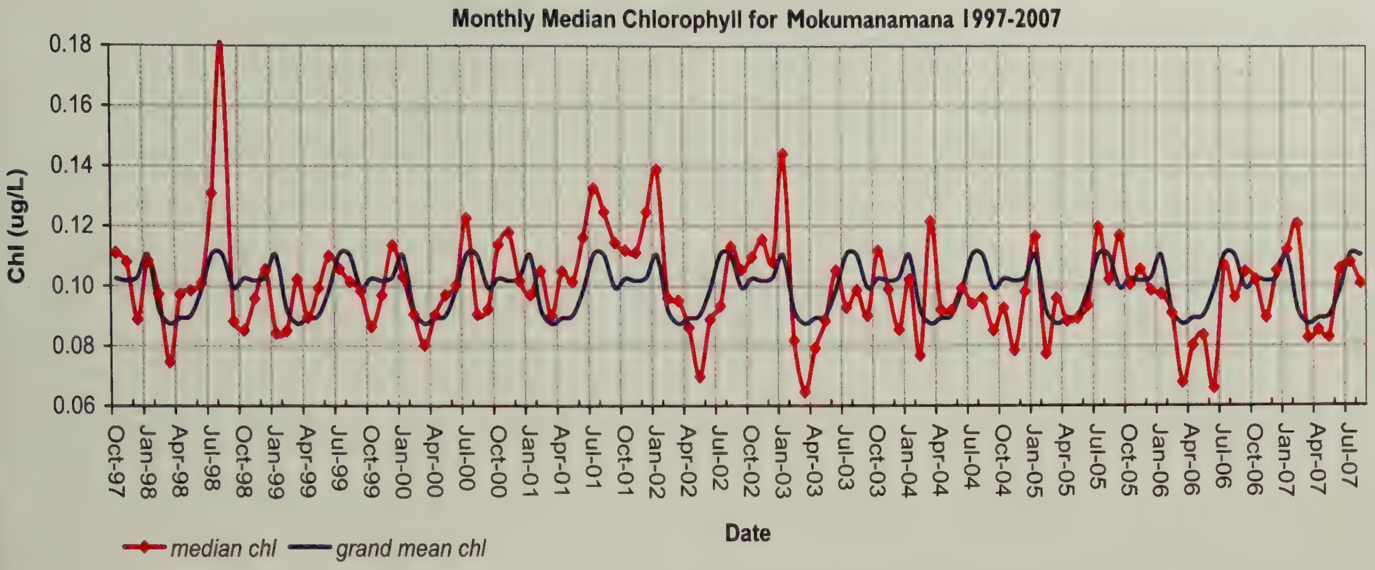


Monthly Median Chlorophyll Anomaly, French Frigate Shoals 1997-2007

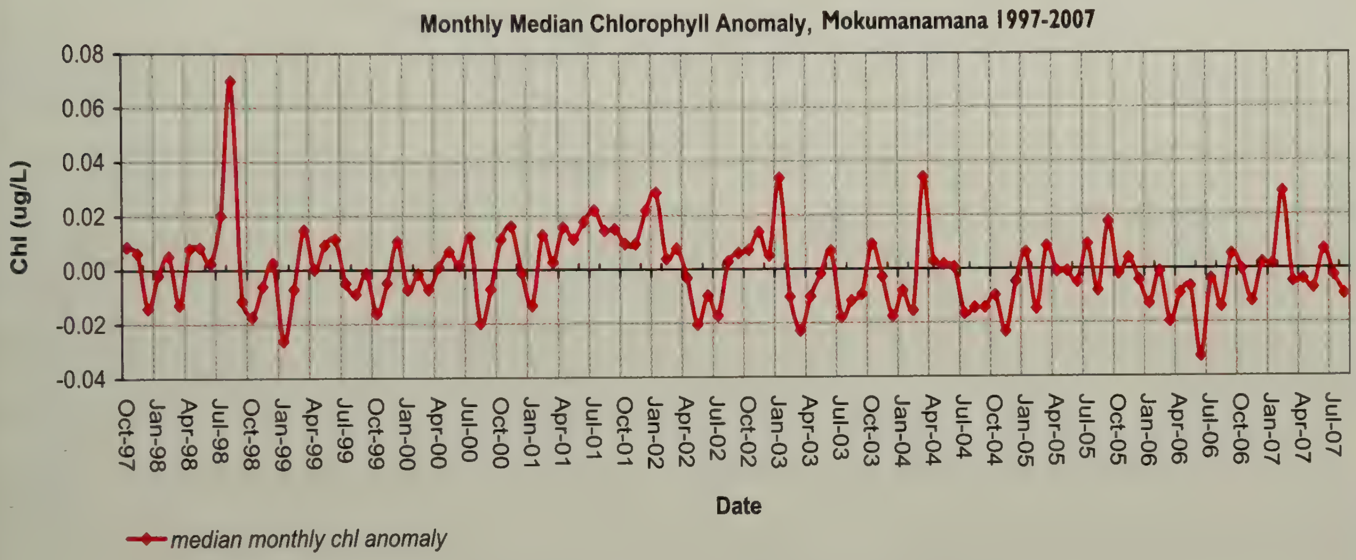


Mean Seasonal Chlorophyll for French Frigate Shoals 1997-2007

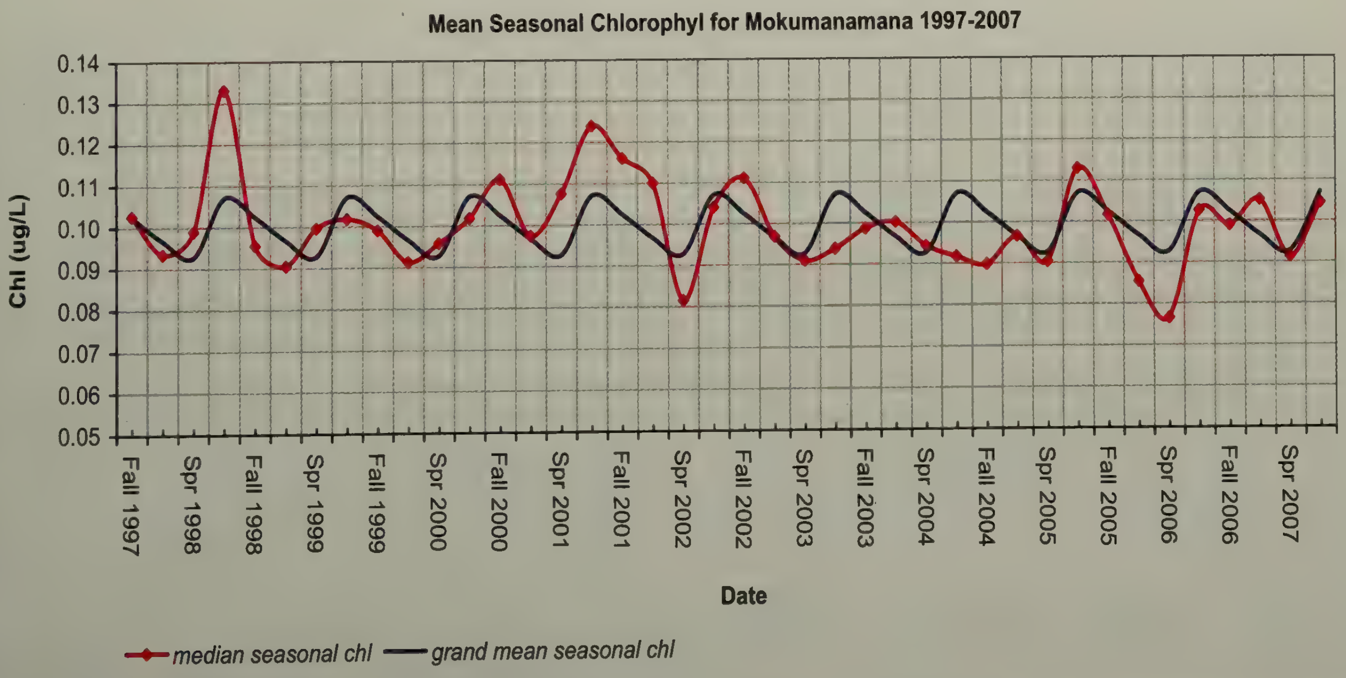




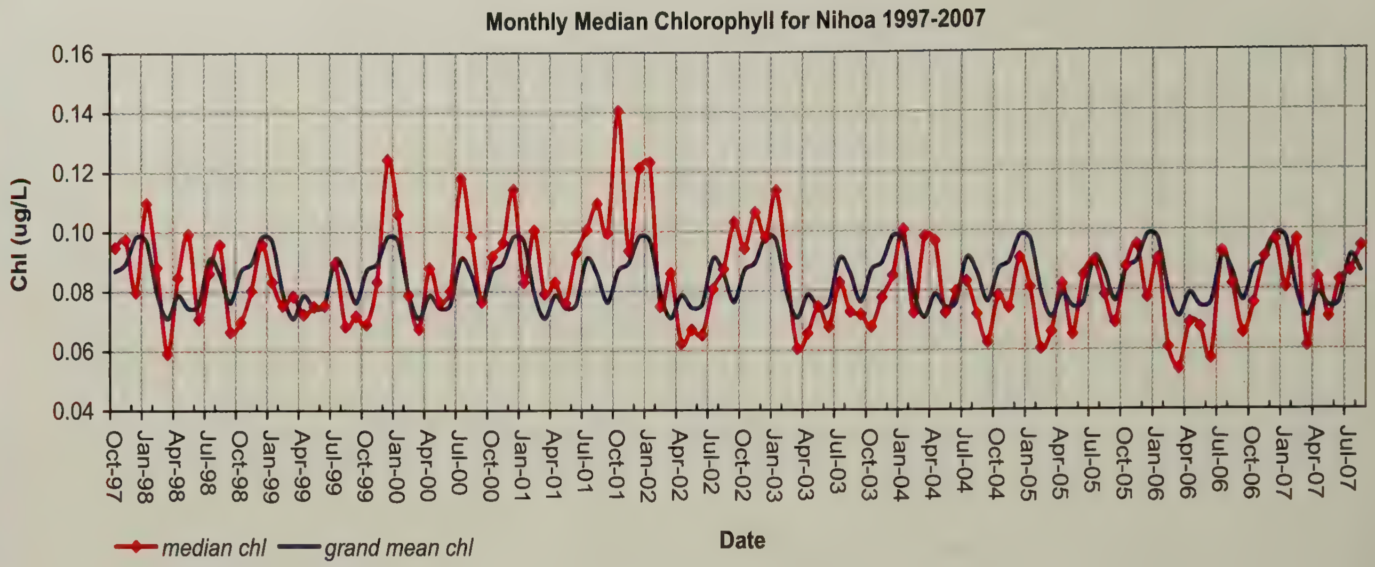
Monthly Median Chlorophyll for Mokumanamana 1997-2007



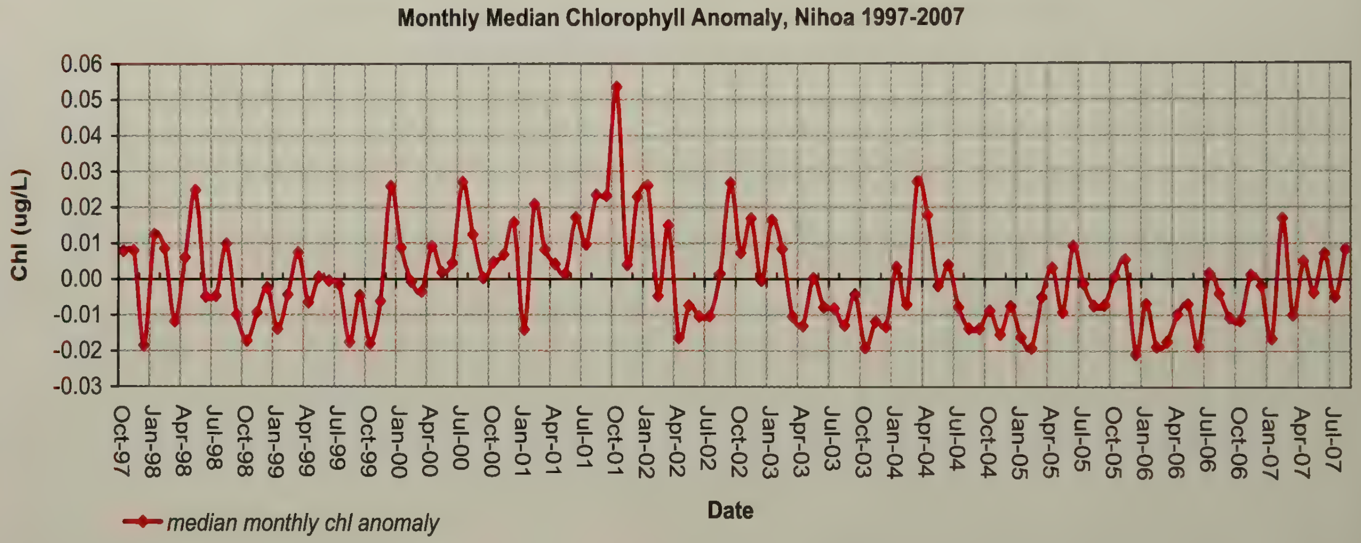
Monthly Median Chlorophyll Anomaly, Mokumanamana 1997-2007



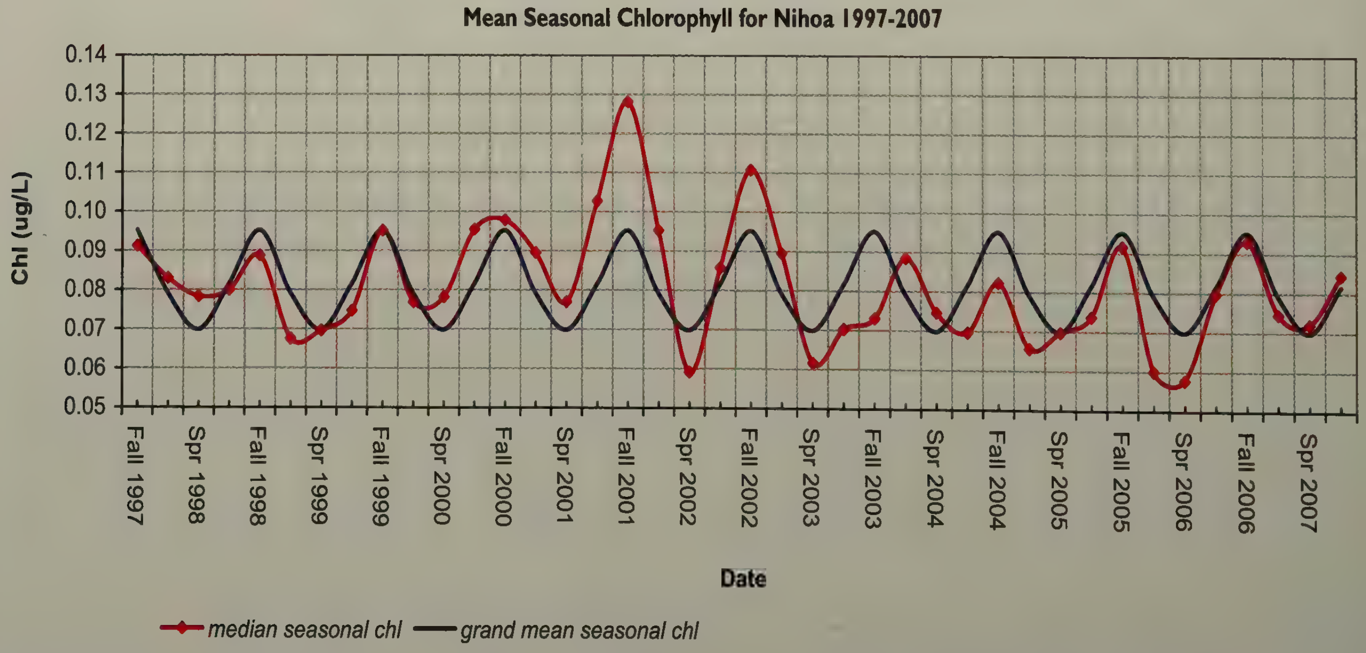
Mean Seasonal Chlorophyl for Mokumanamana 1997-2007



Monthly Median Chlorophyll for Nihoa 1997-2007



Monthly Median Chlorophyll Anomaly, Nihoa 1997-2007



Mean Seasonal Chlorophyll for Nihoa 1997-2007

REFERENCES

Aeby G.S., J.C. Kenyon, J.E. Maragos, and D.C. Potts. 2003. First record of mass coral bleaching in the northwestern Hawaiian Islands. Coral Reefs 22: 256.

Amerson, A.B., R.B. Clapp, and W.O. Wirtz. 1974. Atoll Research Bulletin.

Ashmole, N.P. 1963. The Regulation of Numbers of Tropical Oceanic Birds. British Ornithologists Union Volume 103b:3, pp. 458 - 473.

Ashmole N.P. and M.J. Ashmole. 1967. Comparative feeding ecology of sea birds of a tropical oceanic island. Bulletin of the Peabody Museum of Natural History. 24: 1–131.

Bigelow, K. A., C. H. Boggs, and X. He. 1999. Environmental effects on swordfish and blue shark catch rates in the U.S. North Pacific longline fishery. Fish. Oceanogr. 8: 179-198.

Boehlert, G.W. 1993. Fisheries and marine resources of Hawaii and the U.S.-associated Pacific Islands: An introduction. Marine Fisheries Review. Vol. 55, no. 2, pp. 3-6.

Bograd, S.J., D.G. Foley, F.B. Schwing, C. Wilson, R.M. Laurs, J.J. Polovina, E.A. Howell, and R.E. Brainard. 2004. On the seasonal and interannual migrations of the transition zone chlorophyll front. Geophys. Res. Lett. 31: L17204.

Brainard, R.E., R. Hoeke, R.A. Moffitt, K.B. Wong, J. Firing, J. Gove, S. Choukroun, and K. Hogrefe. 2004. Spatial and temporal variability of key oceanographic processes influencing coral reef ecosystems of the Northwestern Hawaiian Islands [Abst]. Northwestern Hawaiian Islands: 3rd Scientific Symposium. Honolulu, HI. Nov. 2-4 2004, p. 18.

Bromirski, P.D., D.R. Cayan, and R.E. Flick. 2005. Wave spectral energy variability in the northeast Pacific. J. Geophys. Res., 110: C03005, doi:10.1029/2004JC002398.

Canny, J. 1986. A computational approach to edge detection. Institute of Electrical and Electronic Engineers (IEE). Transactions on pattern analysis and machine intelligence. No. 8. IEEE, New York. pp. 679–698.

Di Lorenzo, E., N. Schneider, K.M. Cobb, K. Chhak, P.J.S. Franks, A.J. Miller, J.C. McWilliams, S.J. Bograd, H. Arango, E. Curchister, T.M. Powell, and P. Rivere. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophys. Res. Lett., 35, L08607, doi:10.1029/2007GL032838.

DeMartini, E.E. and A.M. Friedlander. 2004. Spatial patterns of endemism in shallow-water reef fishes of the North West Hawaiian Islands. Marine Ecology Progress Series Vol. 271: 281-296

Dollar, S.J. 1982. Wave stress and coral community structure in Hawaii. Coral Reefs 1: 71-81.

Dollar, S.J. and R.W. Grigg. 2004. Anthropogenic and natural stresses on selected coral reefs in Hawaii: A multidecade synthesis of impact and recovery. Pac. Sci. 58(2): 281-304.

Feare, C.J. 1976. Desertion and abnormal development in a colony of Sooty Terns infested by virus-infected ticks. Ibis. 118: 112–115.

Firing, J.B., R. Brainard, and E. Firing. 2004a. Ten years of shipboard ADCP measurements along the Northwestern Hawaiian Islands. Northwestern Hawaiian Islands: 3rd Scientific Symposium, Honolulu. 18 pp.

Firing, J.B., R. Hoeke, R.E. Brainard, and E. Firing. 2004b. Connectivity in the Hawaiian Archipelago and beyond: potential larval pathways. pp. 310. In: Proceedings of the 10th International Coral Reef Symposium, Okinawa.

Flint, E. 1991. Time and energy limits to the foraging radius of sooty terns *Sterna fuscata.* Ibis. 133: 43-46.

Friedlander, A., G. Aeby, R. Brainard, A. Clark, E. DeMartini, S. Godwin, J. Kenyon, R. Kosaki, J. Maragos, and P. Vroom. 2005. The State of the Coral Reef Ecosystem of the Northwestern Hawaiian Islands. pp. 270-311. In: J.E. Waddell (ed.). The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2005. NOAA Technical Memorandum NOS NCCOS 11. Silver Spring, MD. 522 pp.

Fu, L.-L. 2004. The interannual variability of the North Atlantic Ocean revealed by combined data from TOPEX/Poseidon and Jason altimetric measurements. Geophys. Res. Lett., 31, L23303.

Fu, L.-L., E.J. Christensen, C.A. Yamarone Jr., M. Lefebvre, Y. Ménard, M. Dorrer, and P. Escudier. 1994. TOPEX/POSEIDON mission overview, J. Geophys. Res. 99(C12), 24,369–24,381.

Giambelluca, T.W. and T.A. Schroeder. 1998. Climate. In Atlas of Hawaii (eds. S.P. Juvik and J.O. Juvik). University of Hawaii Press, Honolulu.

Gilson J., D. Roemmich, B. Cornuelle, and L.L. Fu. 1998. The Relationship of TOPEX/POSEIDON altimetric height to the steric height of the sea surface. J. Geophys. Res. 103: 27947-27965.

Hoeke R., R. Brainard, R. Moffitt, and M. Merrifield. 2006. The role of oceanographic condition and reef morphology in the 2002 coral bleaching event in the Northwest Hawaiian Islands. Atoll Research Bulletin. 543.

Houk P., S. Bograd, and R. van Woesik. 2007. The transition zone chlorophyll front can trigger *Acanthaster planci* outbreaks in the Pacific Ocean: Historical confirmation. J. Oceanogr. Vol. 63(1): 149-154(6).

IFREMER. 2002. QuikSCAT Scatterometer Mean Wind Field Products User Manual. Reference: C2-MUT-W-03-IF. Ver. 1.

Johannes, R.E. 1981. Words of the Lagoon: Fishing and marine lore in the Palau District of Micronesia. University of California Press, Berkeley.

Johnson, G.C., M.J. McPhaden, G.D. Rowe, and K.E. McTaggert. 2000. Upper equatorial Pacific Ocean current and salinity variability during the 1996—1998 El Niño-La Niña cycle. J. Geophys. Res. 105: 1037—1053.

Jokiel, P.L. and S.L. Coles. 1990. Response of Hawaiian and other Indo-Pacific reef corals to elevated temperatures associated with global warming. Coral Reefs 8: 155-162.

Jokiel, P.L. and E.K. Brown. 2004. Global warming, regional trends and inshore environmental conditions influence coral bleaching in Hawaii. Global Change Biol. 10: 1627-1641.

Jones, M.S., M. Allen, T. Guymer, and M. Saunders. 1998. Correlations between altimetric sea surface height and radiometric sea surface temperature in the South Atlantic. J. Geophys. Res. 103(C4): 8073–8087.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph. 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bull. Amer. Meteor. Soc. 77: 437–471.

Kazmin, A.S. and M.M. Rienecker. 1996. Variability and frontogenesis in the large-scale oceanic frontal zones. J. Geophysical Research 101 (C1), 907-921.

Kenyon, J.C., G.S. Aeby, R.E. Brainard, J.D. Chojnacki, M.J. Dunlap, and C.B. Wilkinson. 2006. Mass coral bleaching on high-latitude reefs in the Hawaiian Archipelago. pp: 631-634. In: Proceedings of the 10th International Coral Reef Symposium Okinawa 2. Okinawa, Japan. 1,950 pp.

Kenyon, J.C. and R.E. Brainard. 2006. Second recorded episode of mass coral bleaching in the Northwestern Hawaiian Islands. Atoll Research Bulletin 543: 505-523.

Laurs, R.M., P.C. Fiedler, and D.R. Montgomery. 1984. Albacore tuna catch distribution relative to environmental features observed from satellites. Deep-Sea Res., 31(9): 1085-1099.

Leonard, C.L., R.R. Bidigare, M.P. Seki, and J.J. Polovina. 2001. Interannual mesoscale physical and biological variability in the North Pacific Central Gyre. Progress In Oceanography 49(1-4): 227-244.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific decadal climate oscillation with impacts on salmon. Bulletin of the American Meteorological Society. 78: 1069-1079.

NASA. 2004. AVHRR Oceans Pathfinder Sea Surface Temperature Datasets. [Available online] http://podaac.jpl.nasa.gov:2031/DATASET_DOCS/avhrr_pathfinder_sst_v5.html.

NASA. 2005. AVHRR Pathfinder Documentation. [Available online] http://podaac.jpl.nasa.gov/DATA_CATALOG/avhrrinfo.html.

NOAA, NOS, SPO. 1999. Coastal Assessment Framework. Silver Spring, MD.

NOAA. 2004. NOAA-CIRES Climate Diagnostics Center. [available online] http://www.cdc.noaa.gov/.

NOAA. 2005. National Data Buoy Center. [available online] http://www.ndbc.noaa.gov/.

National Weather Service. 2007. Cold and warm episodes by season. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.

Nakamura, H. and A.S. Kazmin. 2003. Decadal changes in the North Pacific oceanic frontal zones as revealed in ship and satellite observations. J. Geophysical Research 108 (C3). 3078. doi:10.1029/1999JC000085.

Papahanaumokuakea Marine National Monument Management Plan: Environmental Assessment Volume II. 2008. NOAA, U.S. Fish & Wildlife Service, and the State of Hawaii. 264 pp.

Philander, S.G. 1990. El Niño, La Niña and the Southern Oscillation. Academic Press. San Diego, CA. 293 pp.

Polovina, J.J., D.R. Kobayashi, D.M. Ellis, M.P. Seki, and G.H. Balazs. 2000. Turtles on the edge: movement of loggerhead turtles (*Caretta caretta*) along oceanic fronts in the central North Pacific, 1997–1998. Fisheries Oceanography 9: 71–82.
Polovina, J.J. and Haight. 1999. Climate variation, ecosystem dynamics, and fisheries management in the NWHI. Ecosystem Approaches for Fisheries Management. Alaska Sea Grant College Program AK-SG-99-01.

Polovina J.J., E. Howell, D.R. Kobayashi, and M.P. Seki. 2001. The Transition Zone Chlorophyll Front, a dynamic global feature defining migration and forage habitat for marine resources. Progress in Oceanography 49(1–4): 469–483.

Polovina, J.J., G.T. Mitchum, N.E. Graham, M.P. Craig, E.E. DeMartini, and E.N. Flint. 1994. Physical and biological consequences of a climate event in the central North Pacific. Fish.Oceanogr. 3: 15–21.

Polovina J.J., G.T. Mitchum, and G.T. Evans. 1995. Decadal and basin-scale variation in mixed layer depth and the impact on biological production in the Central and North Pacific, 1960–88. Deep-Sea Research 42: 1701–1716.

Polovina, J.J. 2005. Climate variation, regime shifts, and implications for sustainable fisheries. Bull. Mar. Sci. 76: 233-2144.

Polovina, J.J. and E. Howell. 2005. Ecosystem indicators derived from satellite remotely sensed oceanography data for the North Pacific. ICES. J. Marine Science 62: 319-327.

Polovina, J.J., E. Howell, D.R. Kobayashi, and M.P. Seki. 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Prog. Oceanogr. 49(1-4): 469-483.

Qiu, B. 1999. Seasonal eddy field modulation of the North Pacific Subtropical Countercurrent: TOPEX/Poseidon observations and theory. J. Phys. Oceanogr. 29: 1670-1685.

Roemmich, D. and J. Gilson. 2001. Eddy transport of heat and thermocline waters in the North Pacific: a key to interannual/decadal climate variability? J. Phys. Oceanogr. 13: 675-687.

Savidge, G. 1976. A preliminary study of the distribution of chlorophyll a in the vicinity of fronts in the Celtic and western Irish Sea. Estuarine, Coastal and Marine Science 4: 617–625.

Savidge, G. and P. Foster. 1978. Phytoplankton biology of a thermal front in the Celtic Sea. Nature 271: 155–157.

Seki, M.P., J.J. Polovina, R.E. Brainard, R.R. Bidigare, C.L. Leonard, and D.G. Foley. 2001. Biological enhancement at cyclonic eddies tracked with GOES thermal imagery in Hawaiian waters. Geophys. Res. Letters. 28(8): 1583-1586.

Seki, M.P., J.J. Polovina, D.R. Kobayashi, R.R. Bidigare, and G.T. Mitchum. 2002. An oceanographic characterization of swordfish (*Xiphias gladius*) longline fishing grounds in the springtime subtropical North Pacific. Fisheries Oceanography 11(5): 251-266(16).

Stumpf, R.P., R.A. Arnone, R.W. Gould, Jr., P. Martinolich, and V. Ransibrahmanakul. 2002. A Partially-Coupled Ocean-Atmosphere Model for Retrieval of Water-Leaving Radiance from SeaWiFS in Coastal Waters: In: Patt, F.S., and et al., 2002: Algorithm Updates for the Fourth SeaWiFS Data Reprocessing. NASA Tech. Memo. 2002-206892, Vol. 22, S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland.

Stumpf, R.P., M.E. Culverb, P.A. Testerc, M. Tomlinsona, G.J. Kirkpatrickd, B.A. Pedersond, E. Trubye, V. Ransibrahmanakulf, and M. Soracco. 2003. Monitoring *Karenia brevis* blooms in the Gulf of Mexico using satellite ocean color imagery and other data. Harmful Algae Vol. 2(2): 147-160.

Ullman, D. and P. Cornillon. 1999. Satellite-derived sea surface temperature fronts on the continental shelf off the northeast U.S. coast. J. Geophys. Res. 104(C10): 23459-23478.

Wilson, C. and V. J. Coles. 2005. Global climatological relationships between satellite biological and physical observations and upper ocean properties. J. Geophys. Res. 110, C10001.

Geology and Benthic Habitats

Jonathan Weiss[1,2], Joyce Miller[1,3], Emily Hirsch[1,4], John Rooney[1], Lisa Wedding[5,6] and Alan Friedlander[6,7]

INTRODUCTION AND ORIGIN

The Northwestern Hawaiian Islands (NWHI) are in the middle section of the 6,126 km long Hawaiian–Emperor seamount chain, considered to be the longest mountain chain in the world (Grigg, 1983; Figure 3.1). Over many millions of years, a relatively stationary plume of hot mantle, or hot spot, located below the floor of the Pacific Plate (Grigg 1982, 1997; Rooney et al., 2008) has and continues to erupt at the seafloor creating a chain of volcanoes that comprise the islands, banks, atolls and seamounts of the Hawaiian Archipelago (Figure 3.2). Each begins as a small submarine volcano and over time can grow to reach well above sea level. Eventually the volcanoes cool and subside as they slowly move away from the hot spot in a northwestward direction at about 8 cm/yr (Clague and Dalrymple, 1987).

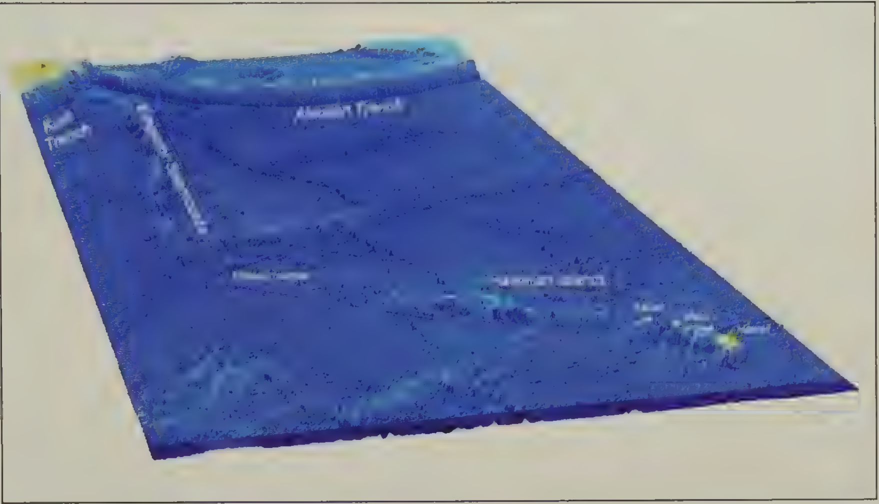


Figure 3.1. Oblique southern perspective of the bathymetry of the Pacific plate between Hawaii and the Aleutian Islands constructed to show the Hawaiian-Emperor Seamount chain and the progressive subsidence of each volcano over time. Sources: Neall and Trewick 2008; image prepared by Jon Procter.

Figure 3.2. The island of Hawaii currently sits over the hot spot that has formed the Hawaiian Archipelago over tens of millions of years. Photo: Hawaii Volcano National Park.

The tops and edges of the volcanoes, if they are at or near sea level, support large and diverse coral reef communities. As the volcanic edifice subsides, an atoll can form as reef builders keep the top of the volcano near sea level by growing vertically and creating a thick carbonate cap. The Darwin Point marks the threshold where vertical growth, or net accretion, of reef building organisms is zero or negative and the atoll drowns and becomes a guyot (Figure 3.3; Grigg et al., 2008). This point, named after Charles Darwin, who first proposed an evolutionary model for atoll formation in 1836, marks a significant milestone in the life of a Hawaiian volcano. Currently Kure Atoll lies very near its Darwin Point. It is the oldest Hawaiian island still above sea level although it consists of only 1 km^2 of emergent land and 66 km^2 of lagoon (Juvik and Juvik, 1998). Dozens of seamounts and guyots extend from north of Kure to the Aleutian Trench and mark the ancient remnants of volcanoes similar to those that comprise the Hawaiian Archipelago (Davies et al., 1972).

---

1. NOAA/NMFS/Pacific Islands Fishery Science Center, Coral Reef Ecosystem Division
2. University of Hawaii Department of Geology and Geophysics
3. Joint Institute for Marine and Atmospheric Research
4. Aquatic Farms Ltd.
5. University of Hawaii at Manoa
6. NOAA/NOS/NCCOS/CCMA Biogeography Branch
7. The Oceanic Institute

General Description of the Archipelago

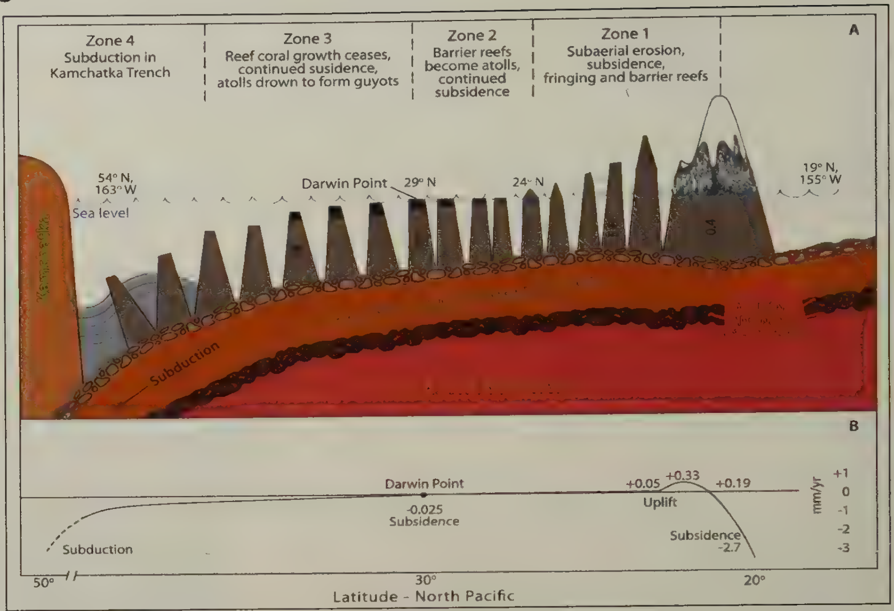


Figure 3.3. Reef accretion across the Hawaiian Archipelago. Note that the net accretion rate diminishes to zero just beyond Kure Atoll, thereby defining a threshold for atoll formation known as the Darwin Point beyond which atolls drown. Source: Grigg, 1997; image: S. Hile.

The youngest and largest of the emergent Hawaiian Islands is the island of Hawaii, which is composed of five volcanoes including the currently active Kilauea Volcano and Mauna Loa and Mauna Kea, which are the two massive shield volcanoes that form the bulk of the island (Figure 3.4). They both extend from the seafloor at >5,000 m below sea level to >4,000 m above sea level and Mauna Kea is the single largest mountain on Earth. Loihi is the youngest submarine volcano in the archipelago and is located 30 km southeast of Hawaii Island. Northwest of Hawaii Island the islands of Maui, Lanai, Kahoolawe and Molokai, make up the island cluster known as "Maui Nui". The highest point in Maui Nui is Haleakala volcano on Maui at 3,055 m. Further northwest is Oahu, the most densely populated island in the chain. Kauai, the Garden Isle, is approximately 5.1 million years old and is deeply eroded with lush vegetation and steep cliffs (Juvik and Juvik, 1998). Niihau and Lehua, which lie 27.7 km southwest of Kauai, are far drier than their larger and higher elevation neighbor, Kauai. Lehua is a private island inhabited by an isolated population of native Hawaiians and access to the island is strictly controlled. Kaula Rock, an uninhab-

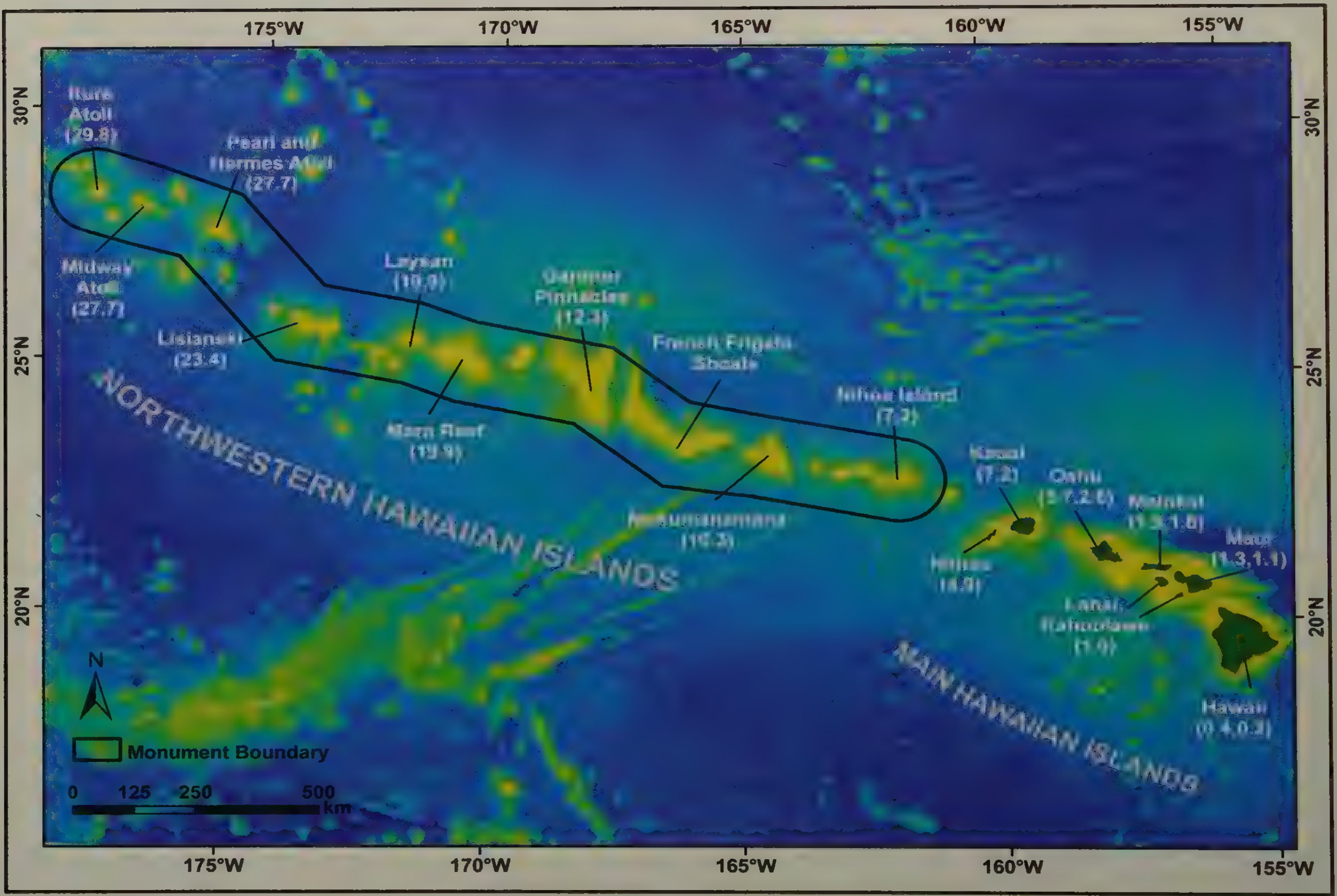


Figure 3.4. Islands, banks and atolls of the Hawaiian Archipelago.

ited island southwest of Niihau, marks the transition between the main or windward islands and the northwestern or leeward islands. The two thousand km of ocean between Kaula Rock and Kure Atoll separates the 10 islands and atolls in the NWHI and a few small emergent pieces of land with a total area of just over 15 km² (Juvik and Juvik, 1998). Northwest of Mokumanamana and Nihoa, are remnant basaltic pinnacles including La Perouse Pinnacle at French Frigate Shoals and the Gardner Pinnacles. The maximum elevation of the islands northwest of Gardner Pinnacles does not exceed 12 m and on some atolls or islands only reaches 3 m.

Table 3.1 shows the land areas of all emergent islands in the NWHI, as well as the submerged marine area encompassed by the 10-fathom (18.29 m) and 100-fathom (182.9 m) isobaths. Within 10 fathoms total shallow water habitats constitute 1,595 km², including the area within lagoons. The area of shallow water habitats within the 100 fathom isobath is 13,771 km². However, these numbers are representative of a two dimensional surface and do not truly convey the surface area of the benthos, which, due to the 3-D topographic complexity of the seafloor, is actually substantially greater. Accurate bathymetric data for the NWHI are being collected and synthesized by the NOAA Coral Reef Ecosystem Division, the Hawaii Mapping Research Group, Joint Institute for Marine and Atmospheric Research (JIMAR), and the Hawaii Undersea Research Laboratory, at the University of Hawaii's School of Ocean and Earth Science and Technology.

Table 3.1. Area mapped by aggregated habitat cover type and geographic scale (km²) based upon IKONOS satellite imagery. Source: NOAA, 2003.

ISLAND	LAND AREA (km²)	AREA (km²) <10 FM	AREA (km²) <100 FM
Kaula	0.6	0	70.5
Bank E of Nihoa	Submerged	0	146.9
Nihoa	0.7	5.6	570.8
Bank SW of Nihoa	Submerged	0	336.2
Bank NW of Nihoa	Submerged	0	63.8
Twin Banks	Submerged	2.3	72
Mokumanamana	0.2	9.1	1,557.2
French Frigate Shoals	0.2	469.4	943.4
Southeast Brooks Bank 1	Submerged	0	29.4
Southeast Brooks Bank 2	Submerged	0	142.3
Southeast Brooks Bank 3	Submerged	0	158.5
Southeast Brooks Bank 4	Submerged	0	3.4
Brooks Bank NW of St. Rogatien	Submerged	0	67.8
St Rogatien Bank	Submerged	0	383.1
Gardner Pinnacles	0.02	0.7	2,446.6
Raita Bank	Submerged	16	571.1
Maro Reef	Awash	217.5	1,935.3
Laysan Island	4.1	26.4	584.5
Northhampton Seamounts (4)	Submerged	0	404.3
Pioneer Bank	Submerged	0	434.6
Lisianski Island/Neva Shoal	1.5	215.6	1,246.6
Bank NW of Lisianski	Submerged	0	106.7
Bank SSE of Pearl and Hermes	Submerged	0	5.5
Bank ESE of Pearl and Hermes	Submerged	0	4.8
Pearl and Hermes Atoll	0.3	374.5	816.6
Salmon Bank	Submerged	0	163.2
Gambia Shoal	Submerged	0	0.5
Ladd Seamount	Submerged	54.2	144.1
Midway Atoll	64	85.4	344.1
Nero Seamount	Submerged	25	71.8
Kure Atoll	1.0	90.2	
Bank W of Kure	Submerged	NA	NA
TOTAL AREA		1,591.9	13,805.6

Pre-Holocene Reef History

The Hawaiian–Emperor chain includes at least 129 massive shield volcanoes that formed over the past 85 million years, with volcano ages generally decreasing in age towards the southeast (Jackson et al., 1975; Clague, 1996). The overall age progression of the islands has been confirmed by several studies using radiometric isotopes to date volcanic rocks from islands and seamounts along the chain (Table 3.2; Clague and Dalrymple, 1987; Garcia et al., 1987) although suitable samples for dating many of the NWHI are difficult to obtain. It has been proposed that the frequency of volcano formation has increased over time based on the decrease in volcano spacing over time. It has also been proposed that the islands at the younger end of the chain are also significantly higher than those formed earlier (Clague, 1996).

Table 3.2. Characteristics of the islands, atolls, and some submerged banks in the NWHI , listed in order from the northwest down to the southeast. Note that most of the subaerially exposed islands, sea stacks, and atolls are surrounded by extensive shallow banks. Island ages are from Clague (1996), with values in brackets from K-Ar dated basalt samples, and other ages estimated from geophysical calculations. Lagoon water volumes are from Hoeke et al., 2006.

ISLAND, ATOLL OR BANK	TYPE OF FEATURE	LONGITUDE	LATITUDE	AGE (MA)	REEF EMERGENT LAND (km^2)	LAGOON HABITAT <100 m (km^2)	BACK-REEF/ LAGOON VOLUME (10^3 m^3)	SUMMIT DEPTH (m)
Kure Atoll	Closed atoll	178° 19.55'	28° 25.28'	29.8	0.86	167	141,000	-
Nero Seamount	Bank	177° 57.07'	27° 58.88'	29.1	0.00	17	-	68
Midway Atoll	Closed atoll	177°22.01'	28° 14.28'	[27.7], 28.7	1.42	223	213,000	-
Pearl and Hermes Atoll	Closed atoll	175° 51.09'	27° 51.37'	[20.6], 26.8	0.36	1,166	2,930,000	-
Lisianski Island Neva Shoal	Open atoll	173° 58.12'	26° 4.2'	23.4	1.46	979	242,000	-
Pioneer Bank	Bank	173° 25.58'	26° 0.71'	22.8	0.00	390	-	26
North Hampton Seamounts	Bank	172° 14.08'	25° 26.84'	[26.6], 21.4	0.00	430	-	5
Laysan Island	Carbonate island	171° 44.14'	25° 46.13'	[19.9], 20.7	4.11	57	3,600	-
Maro Reef	Open atoll	170° 38.34'	25° 30.2'	19.7	0.00	1,508	611,000	-
Raita Bank	Bank	169° 30.04'	25° 31.72'	17.9	0.00	650	-	16
Gardner Pinnacles	Basalt sea stacks	167° 59.82'	25° 0.04'	[12.3], 15.8	0.02	1,904	-	-
St. Rogoties Banks	Banks	164° 7.26'	24° 20.0'	14.7	0.00	500	-	22
Brocks Banks	Banks	166° 49.31'	24° 7.03'	[13.0], 13.6	0.00	320	-	20
French Frigate Shoals	Open atoll	166° 10.75'	23° 45.99'	12.3	0.23	733	1,910,000	-
Bank 66	Bank	165° 49.37'	23° 51.86'	11.9	0.00	0	-	120
Mokumanamana	Basalt island	164° 41.90'	23° 34.64'	[10.3], 10.6	0.21	1,538	64.2	-
Twin Banks	Bank	163° 3.78'	23° 13.08'	8.7, 8.3	0.00	9.5	-	53
Nihoa Island	Basalt island	161° 55.25'	23° 3.73'	[7.2], 7.3	0.82	246	-	-

Holocene Reef Development

Using values of island-specific coral community measures from Grigg (1982), vertical rates of reef accretion can also be estimated and are shown for four islands in Figure 3.5. As the figure suggests, Grigg (1982) found that growth rates show a strong latitudinal dependence, with corals in cooler more northerly islands growing more slowly. He also noted that, based on the work of Gross et al. (1969), at least at the more northerly atolls the carbonate contribution from coralline algae is likely to be significantly more than that from corals.

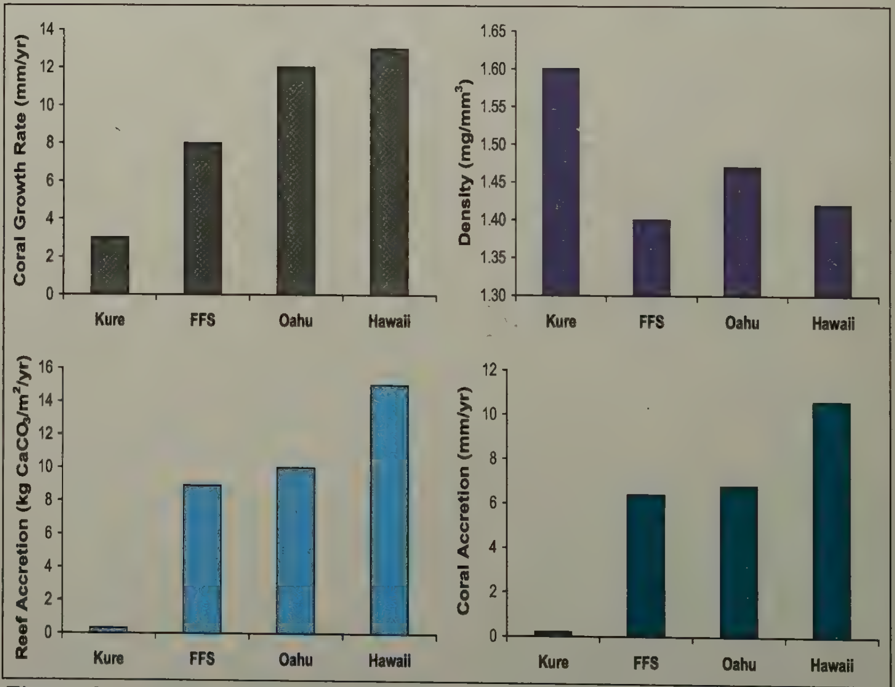


Figure 3.5. Latitudinal variations in coral colony growth rates and reef accretion across the Hawaiian Archipelago. Source: Grigg, 1982.

BENTHIC HABITAT MAPPING

Potential Reef Area

Geographic information system-based analyses were used to derive comprehensive, consistent estimates of the potential area of broadly defined, shallow-water, tropical and subtropical coral ecosystems within the territorial sea and exclusive economic zone of the United States (Rohmann et al., 2005). Nautical charts, published by NOAA's Office of the Coast Survey, provide a consistent source of 10-fathom (ca.18 m) and 100-fathom (ca. 183 m) depth curve information. The 10-fathom or 100-fathom depth curves are used as surrogates for the potential distribution and extent of shallow-water coral ecosystems in tropical and subtropical U.S. waters (Figure 3.6). The NWHI constitute between 4.3% and 12.6% of the total U.S. potential coral reef ecosystem area within 10 fathoms, depending on inclusion versus exclusion of the west Florida shelf area (Rohmann et al., 2005). The NWHI constitute 9.6% of the total U.S. potential coral reef ecosystem area within 100 fathoms, with the inclusion of the west Florida shelf area (Rohmann et al., 2005).

NOAA Mapping Programs

In support of the U.S. Coral Reef Task Force's mission to "Produce comprehensive digital maps of all shallow (<30 m) coral reef ecosystems in the United States and characterize priority moderate-depth reef systems by 2009," NOAA has developed a comprehensive mapping program in the Pacific Region using IKONOS satellite imagery in shallow water (<30 m) and multibeam sonar technology in depths as deep as 3,000 m (Table 3.3). In intermediate depths (10-30 m) IKONOS and multibeam mapping techniques can provide complementary or overlapping coverage. In addition, IKONOS images can be used to create "estimated depths" to fill bathymetric gaps in very shallow water (<15 m) where multibeam vessels cannot safely survey (Stumpf and Holderied, 2003).

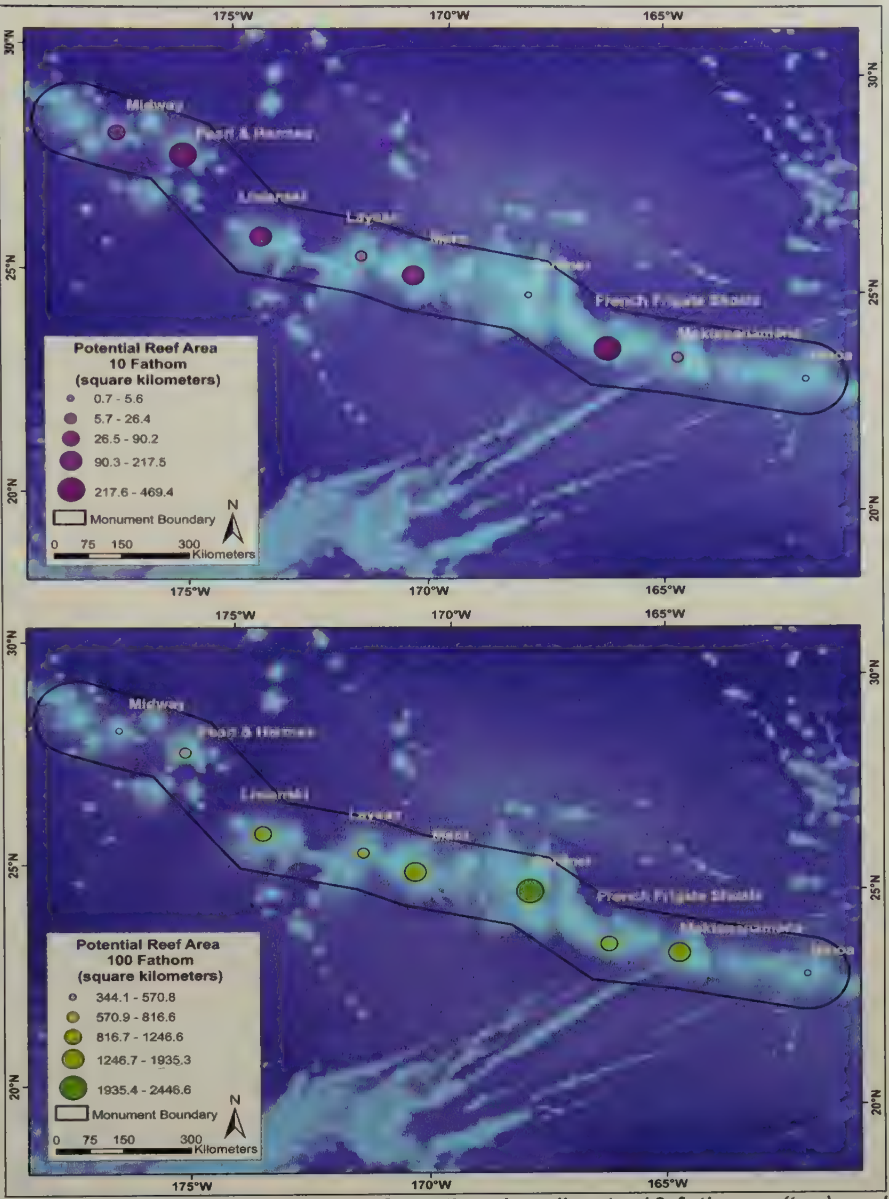


Figure 3.6. Potential reef area from the shoreline to 10-fathoms (top) and 100-fathoms (bottom) based on NOAA nautical charts. Source: Rohmann et al., 2005.

Table 3.3. Area in the NWHI mapped by aggregated habitat cover type based upon IKONOS satellite imagery. Source: NOAA 2003.

AGGREGATED HABITAT COVER TYPE	AREA MAPPED	PERCENT TOTAL
Hardbottom with >10% live coral	108.8	4.61
Hardbottom with >10% crustose coralline algae	7.3	0.31
Hardbottom (uncolonized)	101.4	4.30
Hardbottom with >10% macroalgae	105.2	4.46
Hardbottom with indeterminate cover	822.8	34.85
Unconsolidated with 10% or less macroalgae or seagrass	1,149.6	48.70
Unconsolidated with >10% macroalgae or seagrass	65.8	2.79
Total Habitat Area Classified	**2,360.8**	**100.00**

Shallow Water IKONOS Satellite Mapping

NOAA's Biogeography Branch has sponsored a shallow water (0-30 m) benthic habitat mapping program using IKONOS satellite imagery, which in 2003 produced the Atlas of the *Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands* (available at http://ccma.nos.noaa.gov/ecosystems/coralreef/nwhi/welcome.html). IKONOS high-resolution satellite imagery was used to derive benthic habitat maps, estimated depth, and the color images. The detailed benthic habitat classification scheme was designed to categorize benthic habitat by substrate category (e.g., unconsolidated and hardbottom), structure (e.g., linear reef or pavement) and cover (e.g., coral or macroalgae; Figure 3.7, Table 3.4; http://biogeo.nos.noaa.gov). Of the area mapped, 49% was unconsolidated sediment while 35% was indeterminate.

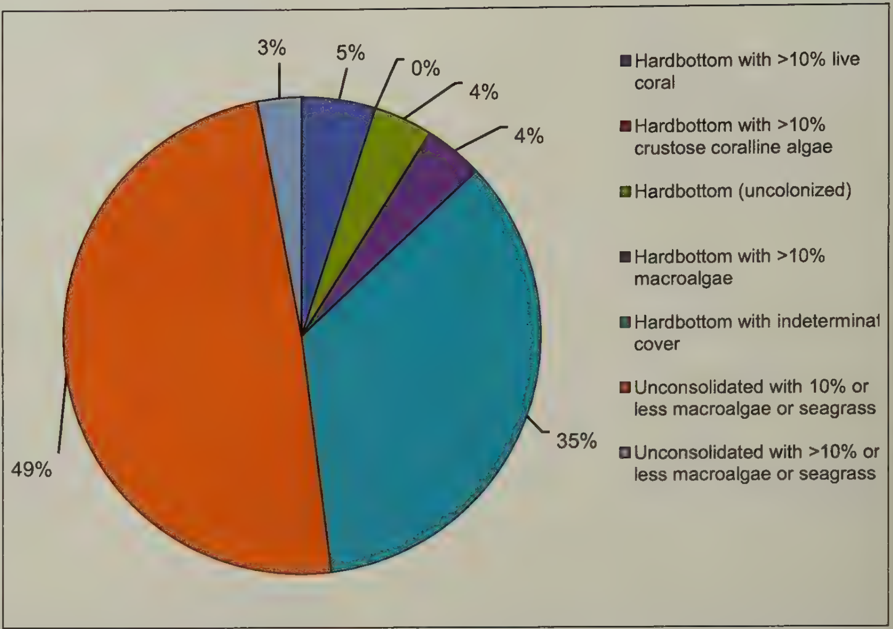


Figure 3.7. Area in the NWHI mapped by aggregated habitat cover type based upon IKONOS satellite imagery. Source: NOAA, 2003.

Table 3.4. Area mapped by aggregated habitat cover type and geographic scale (km²) based upon IKONOS satellite imagery. Source: NOAA, 2003.

TOTAL	KURE ATOLL	MIDWAY ATOLL	PEARL & HERMES ATOLL	LISIANSKI ISLAND	LAYSAN ISLAND	MARO REEF	FRENCH FRIGATE SHOALS	MOKUMANA-MANA	NIHOA ISLAND
Hardbottom with >10% live coral	1.8	1.4	20.3	16.4	5.8	14.8	48.3	0	0.1
Hardbottom with >10% crustose coralline algae	0.7	0.1	0	0	0.5	1.3	4.7	0	0
Hardbottom (uncolonized)	11.6	14.9	13.7	0.9	2.9	6.8	49.9	0	0.7
Hardbottom with >10% macroalgae	5.8	22.4	62.2	6.1	0.1	0.4	3.7	0	4.5
Hardbottom with indeterminate cover	8.4	6.7	49.3	183.5	81.7	180.1	46.1	208.1	58.9
Unconsolidated with 10% or less macroalgae or seagrass	38.8	49.9	226.2	231.8	36.2	295.7	241.5	19.5	10
Unconsolidated with >10% macroalgae or seagrass	2.7	0.2	19.9	0	0	19.6	23.4	0	0
Total Habitat Area Classified	69.8	95.5	391.6	438.7	127.2	518.7	417.6	227.6	74.1

Moderate-Depth Multibeam Mapping

NOAA's Coral Reef Ecosystem Division (CRED) initiated a moderate-depth multibeam mapping program which was conceived in 2001, implemented between 2002 and 2005, and has produced over 45,000 km² of bathymetric data in the NWHI since 2002 (Table 3.5; Miller et al., 2003). This mapping program is designed to extend and be complementary to the shallow-water IKONOS mapping program discussed above.

In 2002 multibeam surveys to define 25, 50, and 100-fm isobaths in the NWHI were conducted by NOAA and University of Hawaii (UH) personnel aboard UH's R/V *Kilo Moana*, using Kongsberg/Simrad EM1002 and EM120 multibeam sonars (Table 3.5). These surveys resulted in the ring-shaped survey patterns around the banks and atolls that are shown in Figure 3.8. Moderate depth multibeam sonar surveys were conducted in the NWHI between 2003 through 2008 by personnel from CRED, NOAA's Office of National Marine Sanctuaries, and other partners using mapping systems aboard the NOAA Ship *Hiialakai* and the survey launch R/V *Acoustic Habitat Investigator (AHI)*. The *Hiialakai* is equipped with two Kongsberg/Simrad multibeam sonars: a 30-kHz EM300 with mapping capability from approximately 100-3000+ m and a 300-kHz EM3002D with mapping capability from about 5-150 m. The R/V *AHI* has a 240-kHz Reson 8101ER with mapping capability from about 5-300 m. Both vessels have Applanix POS/MV motion sensors, which provide navigation and highly accurate readings of the vessel motion in all axes. Optical validation data have also been collected since 2001 using towed and drop camera systems aboard the *Hiialakai*, *AHI* and the NOAA Ship *Oscar Elton Sette*.

Table 3.5. NWHI multibeam mapping statistics and estimates.

	MAPPING COMPLETED 2002-2008		**ESTIMATE TO COMPLETE**
	km^2	Days	Days Remaining
Deep (100-5,000 m)	41,664	28	67
Mid-Depth (10-100 m)	3,854	134	275
Totals	**45,518**	**162**	**342**

Bathymetric data from these 2003-2008 *Hiialakai* and *AHI* surveys add to previously published data (Miller et al., 2003) from the 2002 R/V *Kilo Moana* surveys as well as estimated depths from IKONOS imagery Figure 3.8 and Table 3.5 show current bathymetric coverage in NWHI.

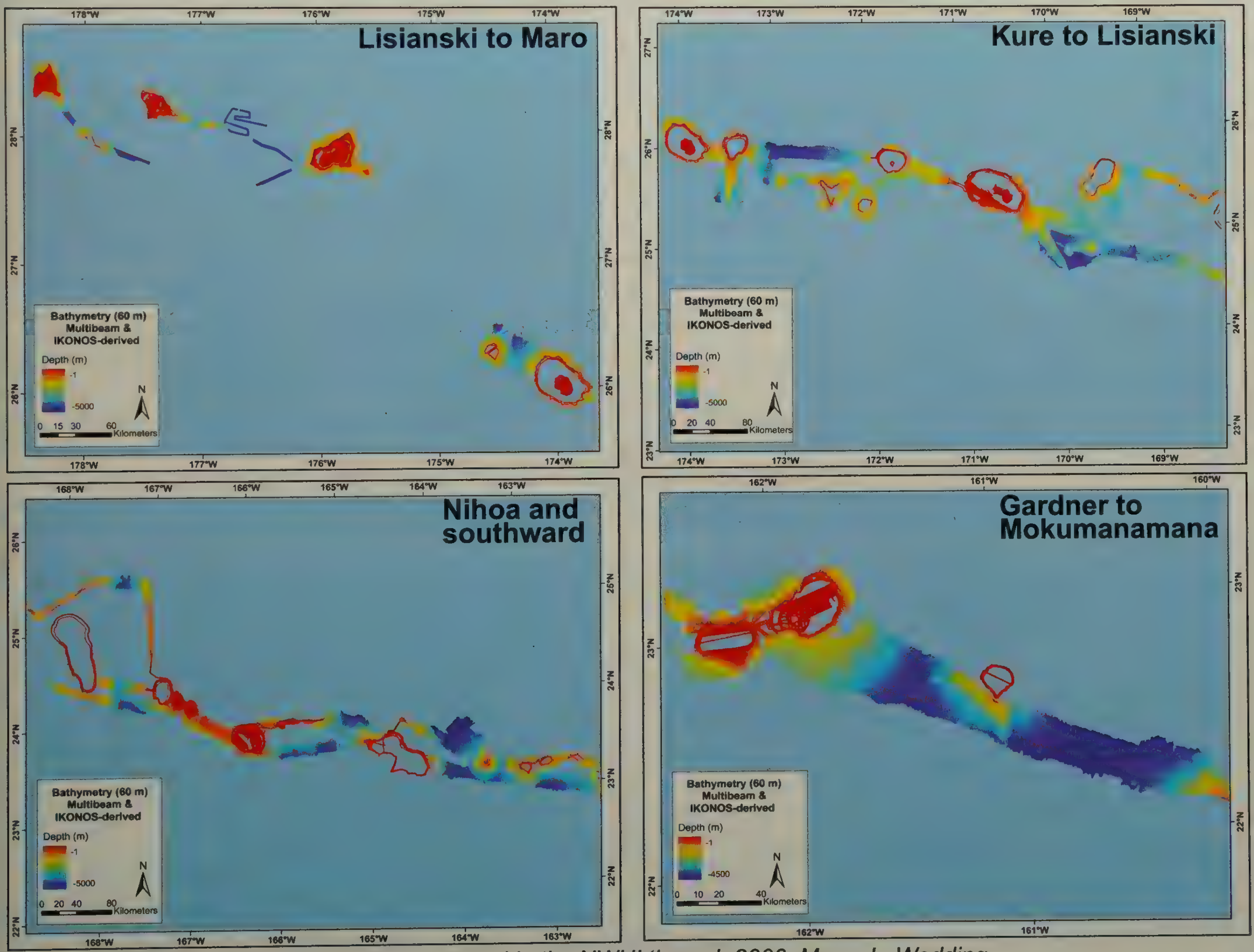


Figure 3.8. Multibeam maps of all data collected in the NWHI through 2006. Maps: L. Wedding.

Bathymetric grids at various resolutions are updated annually and published on the web at the Pacific Islands Benthic Habitat Mapping Center (PIBHMC; www.soest.hawaii.edu/pibhmc). As shown in Figure 3.8, some bathymetric data have been collected and processed at all of the islands and banks in the NWHI in water depths ranging from 3 to 3,000 m with almost complete coverage at Kure, Midway, Pearl and Hermes, Brooks Banks and French Frigate Shoals, and partial coverage at other locations. The bank on the southwest side of French Frigate Shoals was the first area to be mapped in early 2005 and 95% completed in 2008, and this data set is used later in this chapter to illustrate the various benthic habitat mapping products, their potential uses, and interpretation. Similar products for other banks are regularly added to the PIBHMC web site as mapping, data processing, product and metadata generation, and interpretation are completed.

The geomorphological data layers of substrate, slope, rugosity, and bathymetric position index (BPI) produced at the PIBHMC are derived from multibeam bathymetry. Derivative data products (e.g., slope, rugosity and BPI) add geomorphological information about characteristics (e.g., roughness) that may assist in determining benthic habitat utilization. An explanation of each derivative type is given here. At this time a complete set of derivate products has been developed only for French Frigate Shoals.

Rugosity: Cell values reflect the surface area to planimeteric area ratio (surface area) / (planimetric area) for the area contained within that cell's boundaries. This measure provides an index of topographic roughness and convolutedness (Jenness, 2003). Distributions of fish and other mobile organisms are often found to positively correlate with increased complexity of the seafloor. Investigations are underway for the development of the most appropriate spatial metrics for quantifying benthic complexity for the purposes of relating these metrics to fish distributions in Pacific coral reef ecosystems. Results of the Jenness (2003) method are provided as a standardized and well-documented interim product.

Slope: Cell values reflect the maximum rate of change (in degrees) in elevation between neighboring cells.

Substrate: This is a preliminary product that is still under development. Cell values reflect whether the seafloor is hard bottom or soft bottom based on an unsupervised classification run in Environment for Visualizing Images (ENVI) software. The classifications (hard bottom versus soft bottom) are based on backscatter, bathymetry, acoustic derivatives and optical data.

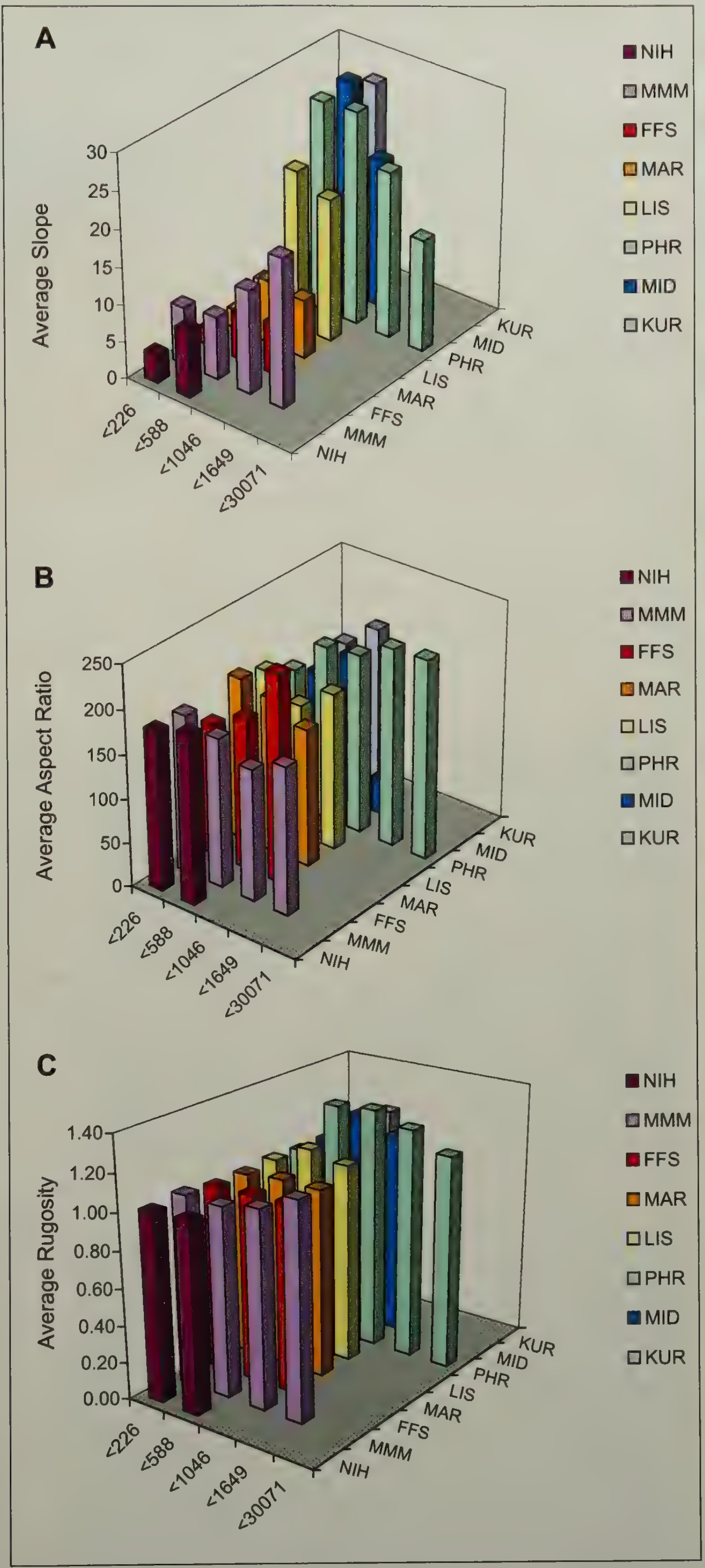
Bathymetric Position Index: BPI is a second order derivative of bathymetry. The derivation evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user defined annulus or circle. A negative value represents a cell that is lower than its neighboring cells (depressions) and a positive value represents a cell that is higher than its neighboring cells (crests). Larger numbers represent more prominent features on the seafloor, which differ greatly from surrounding areas. Flat areas or areas with a constant slope produce near-zero values. (Lundblad et al., 2006).

Summary of Multibeam Data

Based on available multibeam data, summary statistics (slope, aspect ratio and rugosity) were developed for five depth bins based on natural breaks (9-226 m, 226-588 m, 588-1,045 m, 1,045-1,649 m and 1,649-3,071 m). Slope values overall are lowest in the shallow (<226 m) depth bin (Figure 3.9). Islands further upchain such as Kure, Midway, Pearl and Hermes and Lisianski have higher slope values, on average, compared with locations further southeast along the chain. Aspect ratio (Δ Z/ΔX) does not vary greatly by depth bin or among reefs. Rugosity increases slightly with depth and the highest rugosity was found at Pearl and Hermes Atoll.

Island Profiles

The following sections summarize the geologic and benthic habitat information available for each emergent island in the NWHI, as of January 2009. The data include results from both IKONOS satellite imagery and multibeam data analyses.



Figures 3.9. A) Average slope by depth bin from multibeam sonar data collected at select islands within the NWHI; B) Average aspect ratio by depth bin from multibeam sonar data collected at select islands within the NWHI; and C) Average rugosity by depth bin from multibeam sonar data collected at select islands within the NWHI.

Nihoa Island

Nihoa Island is located approximately 249.4 km northwest of Kauai, the closest to the Main Hawaiian Islands (MHI). Measuring roughly 0.68 km², this island is the largest emergent volcanic island within the Monument and the tallest, reaching an elevation of 275.2 m at Miller Peak. It is also the geologically youngest island within the Monument, with an age calculated at 7.3 million years (Clague, 1996). Nihoa is a deeply eroded remnant of a once large volcano, and the large basaltic shelf of which it is a part stretches 28.9 km in a northeast-southwest direction and ranges between 34.1 and 66.1 m deep (NOAA, 2003). The island's two prominent peaks and steep sea cliffs are clearly visible from a distance, rising like a fortress above the sea. The island's northern face is com-

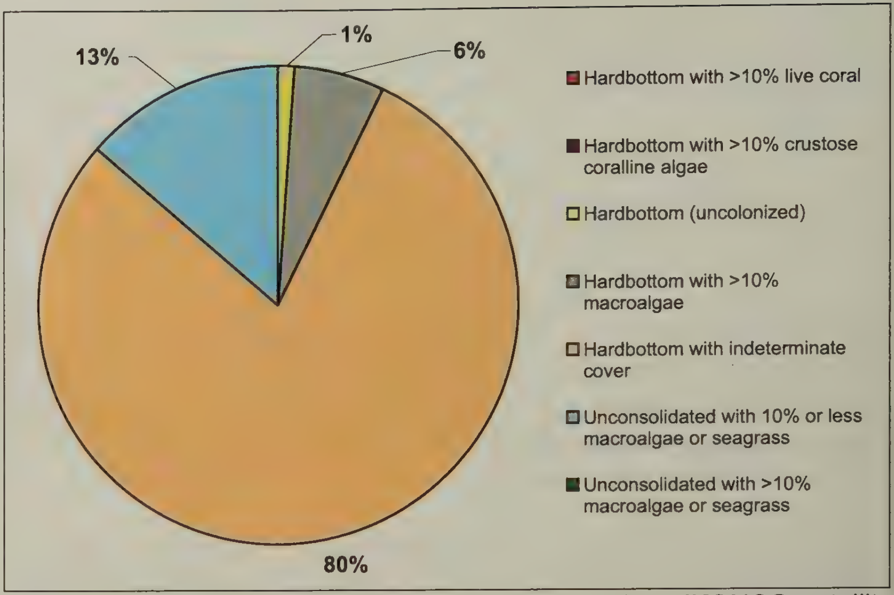


Figure 3.10. Benthic habitats around Nihoa based on IKONOS satellite data. Source: NOAA, 2003.

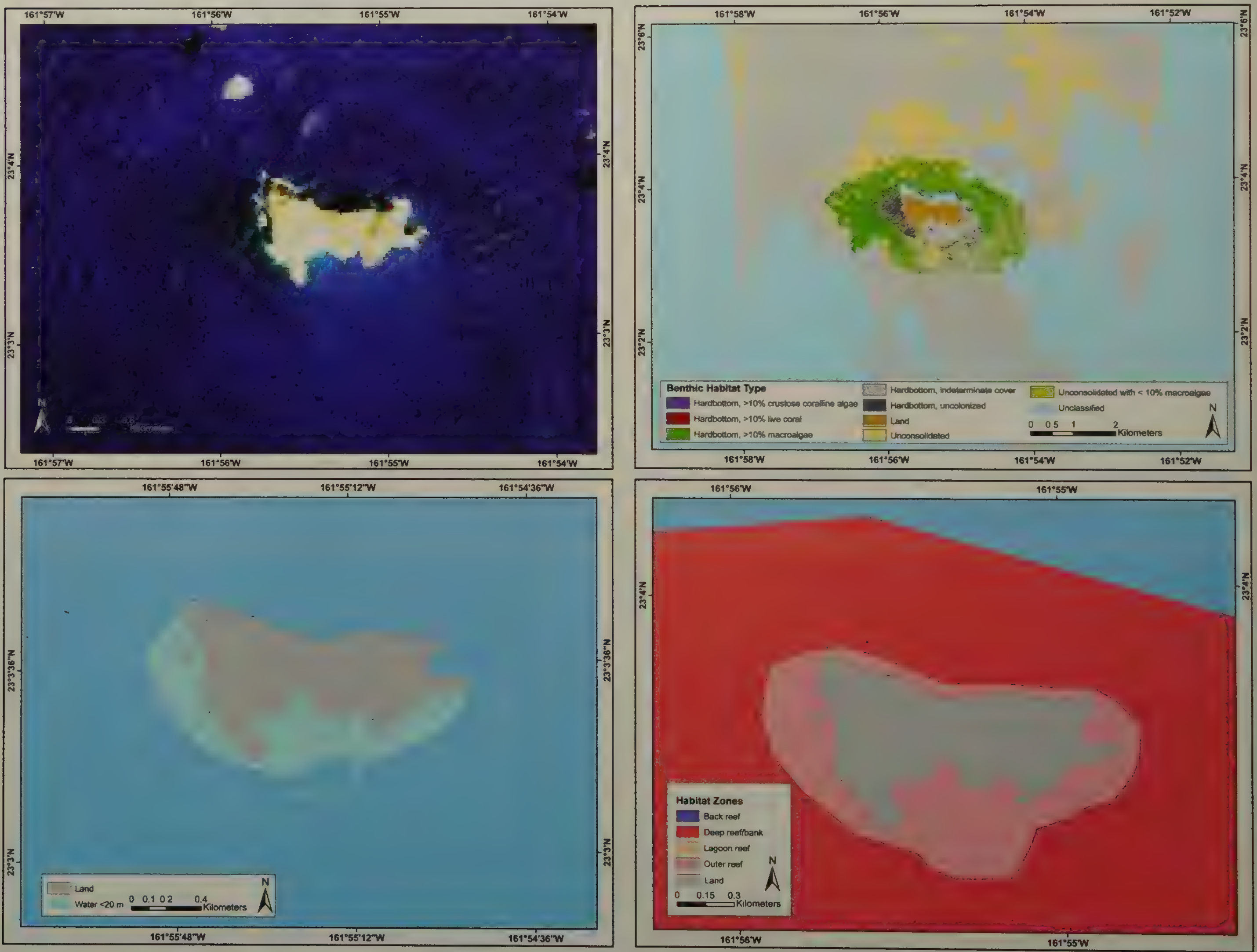


Figure 3.11. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones for Nihoa Island (bottom right). Maps: L. Wedding.

posed of a sheer cliff made up of successive layers of basaltic lava, within which numerous volcanic dikes are visible. The island's surrounding submerged reef habitat totals approximately 574.6 km^2 and is a combination of uncolonized hard bottom, macroalgae, pavement with sand channels and live coral, and uncolonized volcanic rock (NOAA, 2003; Figures 3.10, 3.11). The principal shallow water bottom habitats around Nihoa consist of hard basalt as vertical walls, horizontal wave-cut basalt benches, elevated mounds, and large blocks and boulders. Nihoa supports coral communities with very limited total habitat, most of which is not protected from the heavy and chronic wave action that strikes this small island from all directions. These habitats have been shaped by and are constantly eroded by the pounding waves.

Multibeam surveys were conducted around Nihoa Island and on West Nihoa Bank on several different cruises, including R/V *Kilo Moana* KM-02-06, *Hiialakai* HI-05-01 and *Hiialakai* HI-06-12. The first two survey patterns around Nihoa Island were designed to delineate the 25-, 50-, and/or 100-fm boundaries needed for the National Marine Sanctuary designation process. Slope, aspect, and rugosity all increased with depth although the difference was small (Table 3.6). In Tables 3.6 -3.13 minimum, maximum, range, mean and standard deviation for bathymetry are in meters; slope and aspect are in degrees (0-360); and rugosity is a dimensionless ratio of surface area to planimetric area. High rugosity typically indicates a rough and complex substrate that often correlates with potential coral habitat.

Bathymetry data for all islands was merged into a single raster. This was reclassified into five depth classes using natural breaks - a method which seeks to equalize the variation between each class - in the ArcGIS 9.2 Spatial Analyst extension. Using these 5 classes as zones, zonal statistics were run on bathymetry, slope, aspect and rugosity by island, using the "zonal statistics as table" tool in Spatial Analyst. This resulted in

Table 3.6. Summary statistics for multibeam surveys conducted around Nihoa Island and on West Nihoa Bank.

NIHOA	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	353.68	-225.17	-25.21	199.96	-69.46	41.34
	266 to 588	248.65	-500.00	-225.17	274.82	-356.89	65.18
Slope	9 to 226	-	0.00	68.01	68.01	3.72	7.79
	266 to 588	-	0.00	75.99	75.99	8.96	7.66
Aspect	9 to 226	-	0.00	360.00	360.00	180.02	111.23
	266 to 588	-	-1.00	360.00	361.00	191.13	118.97
Rugosity	9 to 226	-	1.00	2.86	1.86	1.01	0.06
	266 to 588	-	1.00	4.44	3.44	1.03	0.05

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

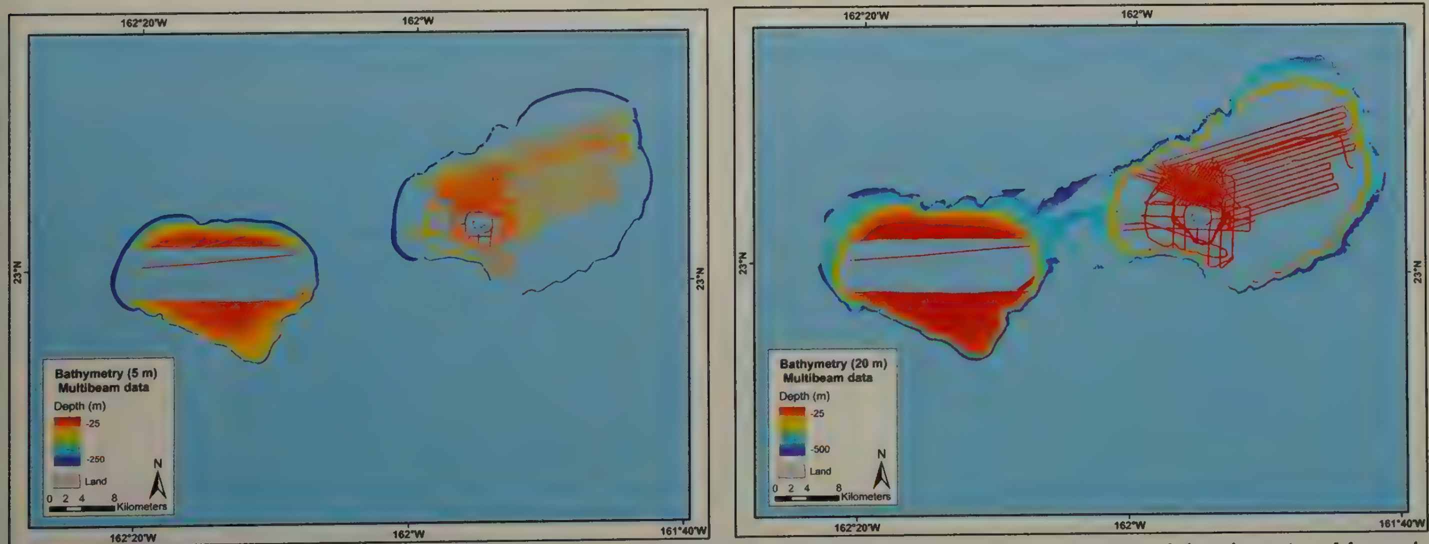


Figure 3.12. 5 m and 20 m bathymetry for Nihoa with derived depths from IKONOS imagery near island center. Maps: L. Wedding.

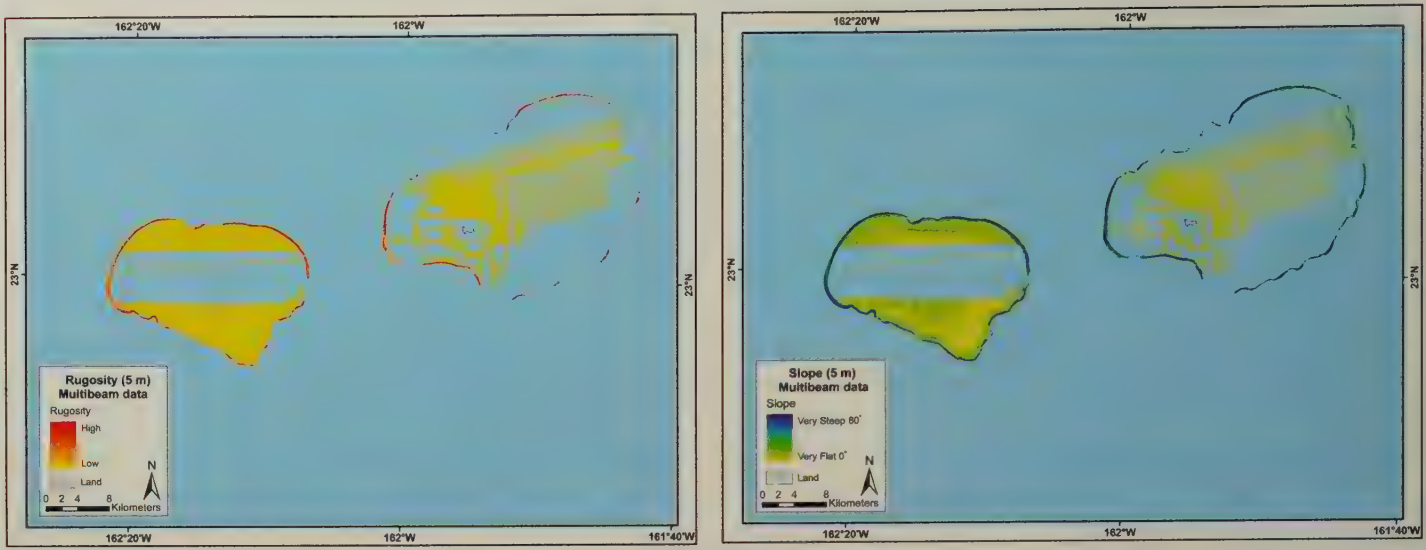


Figure 3.12 (continued). Rugosity (5 m), and slope (5 m) for Nihoa with derived depths from IKONOS imagery near island center. Maps: L. Wedding.

the generation of summary statistics for each island in terms of the NWHI as a whole, making it possible, for example, to compare the average slope of Kure with that of Maro within the same depth class.

Cruise *Hiialakai* HI-06-12 surveys on West Nihoa Bank were conducted to provide continuous coverage in order to better delineate topography on submerged banks; the resulting maps revealed some intriguing features on the southern part of West Nihoa Bank (Figure 3.12). Surveys of bottom fish habitats (Figure 3.13) and fish abundance were also conducted during *Hiialakai* HI-06-12.

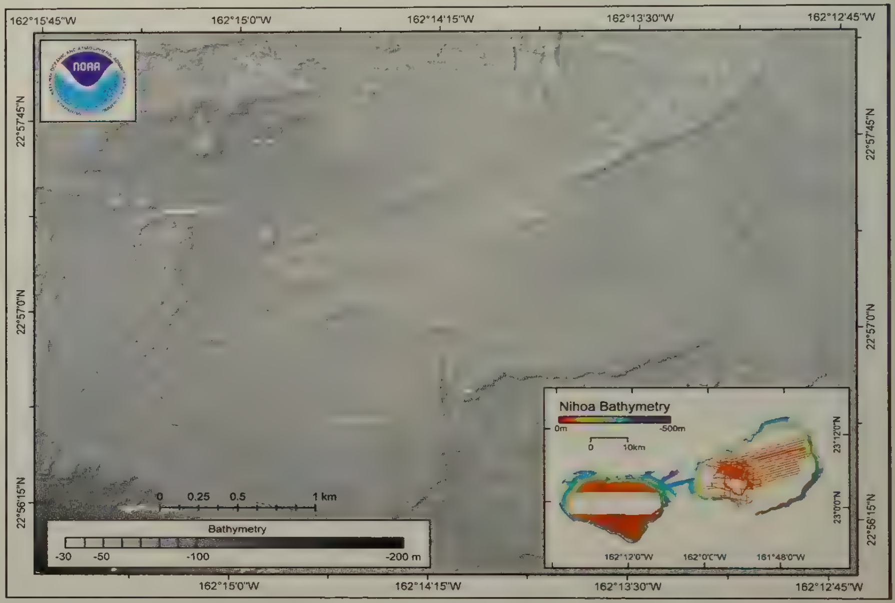


Figure 3.13. Detailed hillshade of bathymetric data on the southern portion of West Nihoa bank.

Mokumanamana Island

Mokumanamana Island is a hook-shaped dry volcanic island that includes about 18 hectares of land with 9.1 km² of potential coral reef habitat within 10 fathoms and a large bank that includes 1,557 km² of habitat within 100 fathoms. Mokumanamana is a dry volcanic island shaped like a fishhook, and includes approximately 0.18 km² of land. Geologists believe the island, with an estimated age of 10.6 million years, was once the size of Oahu in the MHI, with a maximum paleo-elevation of 1,036 m (Clague, 1996), but due to centuries of erosion its highest point, at Summit Hill, is now only 84.1 m above sea level. All shallow

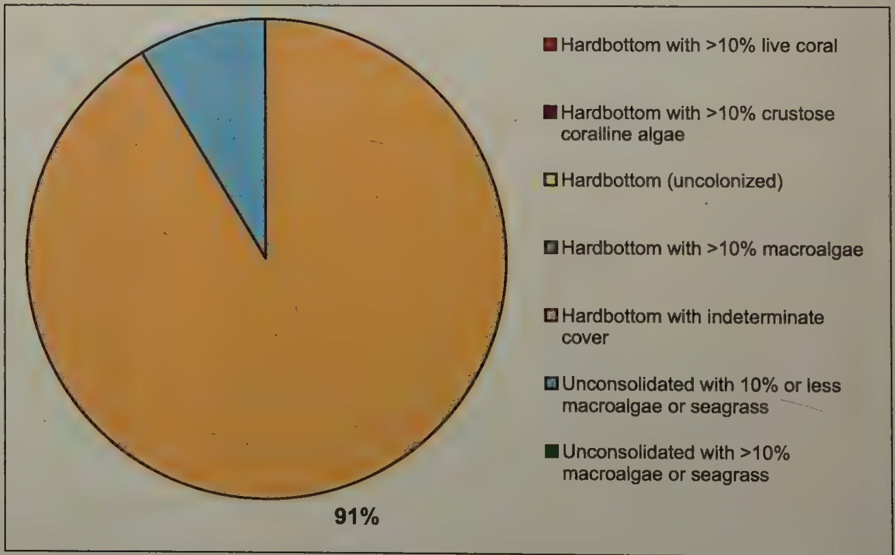


Figure 3.14. Percent composition of mapped benthic habitats at Mokumanamana based on NOAA benthic habitat maps. Source: NOAA, 2003.

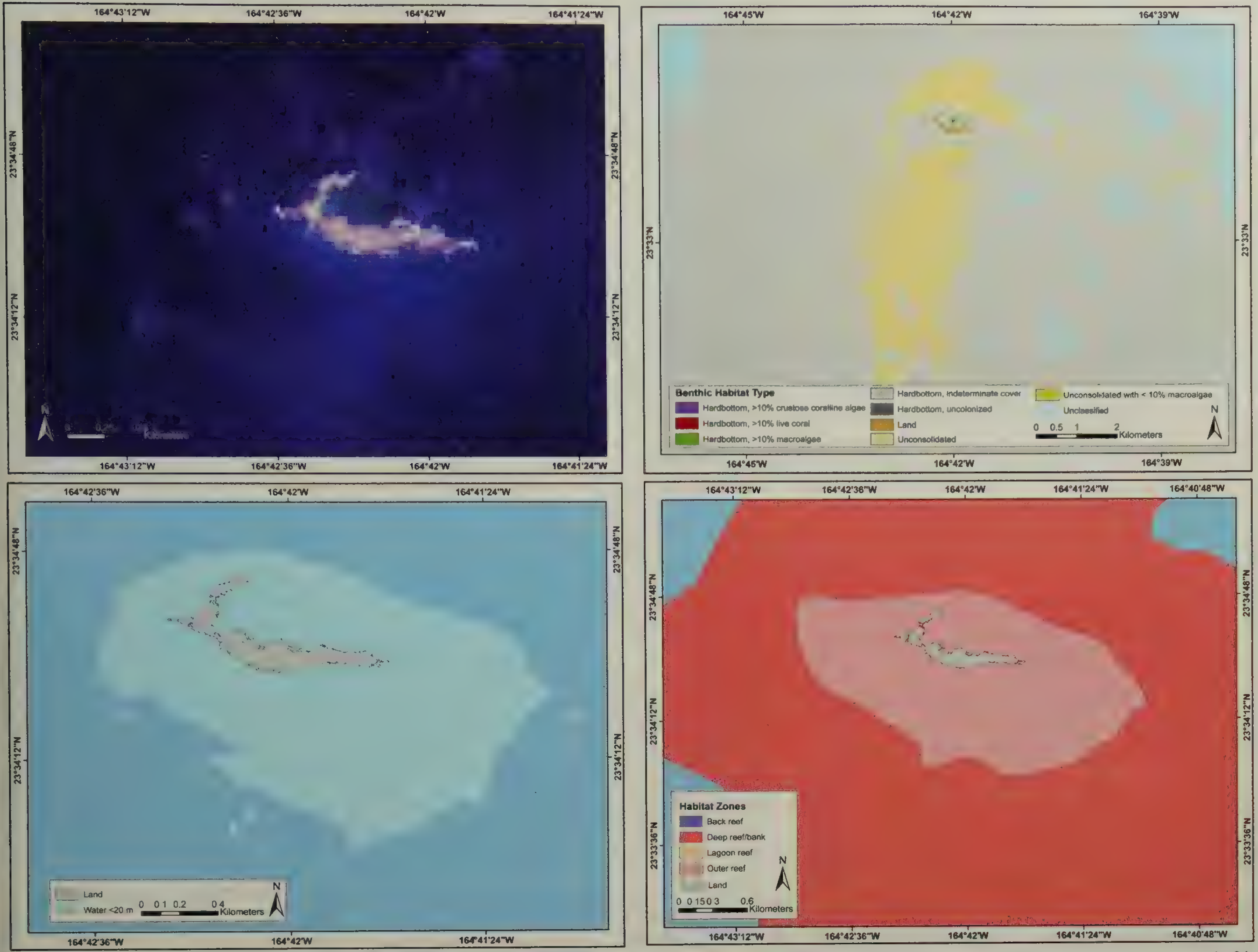


Figure 3.15. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Mokumanamana. Maps: L. Wedding.

Table 3.7. Summary statistics for multibeam surveys conducted around Mokumanamana in 2002.

MOKUMANAMANA	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	202.99	-286.14	-1.03	285.11	-90.93	57.43
	266 to 588	362.93	-737.97	-145.73	592.23	-376.12	88.38
	588 to 1,046	77.04	-1,132.92	-394.30	738.62	-812.10	125.46
	1,046 to 1,649	53.09	-1,500.00	-953.00	547.00	-1,290.05	140.25
Slope	9 to 226	-	0.00	69.72	69.72	7.81	10.13
	266 to 588	-	0.00	77.49	77.49	8.38	8.40
	588 to 1,046	-	0.00	77.45	77.45	13.91	10.48
	1,046 to 1,649	-	0.00	76.94	76.94	20.04	13.80
Aspect	9 to 226	-	-1.00	360.00	361.00	179.46	113.87
	266 to 588	-	-1.00	360.00	361.00	168.49	120.76
	588 to 1,046	-	-1.00	360.00	361.00	149.07	119.73
	1,046 to 1,649	-	-1.00	360.00	361.00	167.43	126.94
Rugosity	9 to 226	-	1.00	3.33	2.33	1.03	0.09
	266 to 588	-	1.00	5.67	4.67	1.03	0.07
	588 to 1,046	-	1.00	4.51	3.51	1.07	0.13
	1,046 to 1,649	-	1.00	4.87	3.87	1.16	0.25

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

marine habitats are basalt surfaces exposed to high wave action and the effects of scour (surge combined with sand and other sediments) is evident from the wave-cut bench in West Cove and the deeply cut sand channels and chasms at several locations in deeper water (Figures 3.14, 3.15). Reef growth in shallow waters, if any, is minimal and the punishing effects of large waves as demonstrated by the high wave cut sea cliffs above sea level and wave planed benches and shelves below sea level. The bank provides excellent habitat for spiny lobsters (*Panulirus marginatus*) and slipper lobsters (*Scyllarides squammosus*), especially in habitats of less than 27.4 m depth and high benthic relief (Parrish and Polovina, 1994).

Multibeam surveys around Mokumanamana were conducted in 2002 (KM0206) and 2008 (HI0804; Table 3.7, Figure 3.16). The 2002 surveys were for 25-, 50-, and/or 100-fm boundary delineation and the survey in 2008 was planned to better delineate the Necker Ridge that runs southwest from Mokumanamana, which is under consideration as a possible extension to the U.S. Exclusive Economic Zone. The data from the 2008 surveys have not yet been fully processed and Figure 3.16 shows only data collected in 2002. Slope and rugosity increase with increasing depth while the aspect ratio is highest in the shallowest depth range (<226 m; Table 3.7).

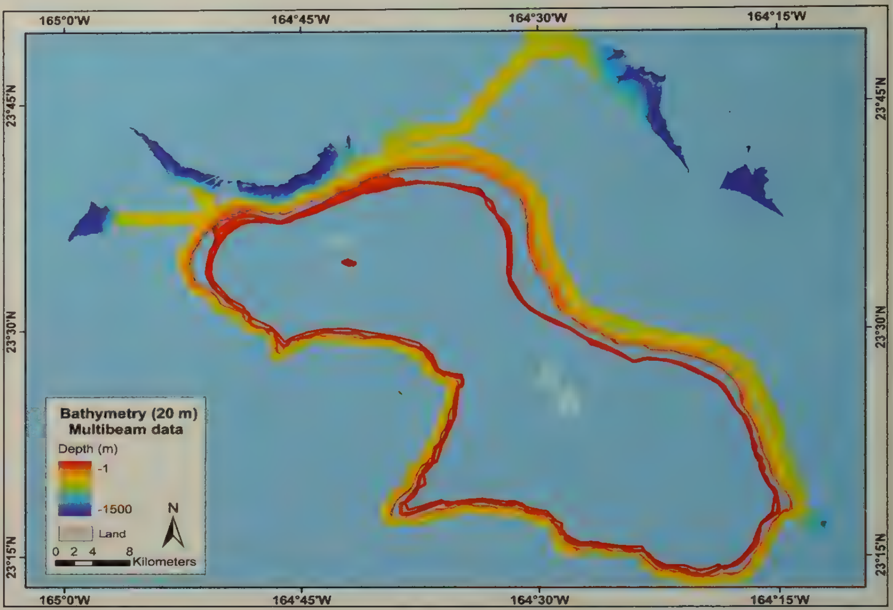


Figure 3.16. Multibeam bathymetric data around Mokumanamana Island collected in 2002 and 2006 derived depths from IKONOS imagery near island center. Map: L. Wedding.

French Frigate Shoals

French Frigate Shoals is the largest atoll in the chain, taking the form of an 28.9 km long crescent. It is estimated to be 12.3 million years old (Clague, 1996). The shoals consist of 0.27 km^2 of total emergent land surrounded by approximately 931 km^2 of coral reef habitat, with a combination of sand, rubble, uncolonized hard bottom, and crustose coralline algae in the windward and exposed lagoon areas, and patch and linear coral reefs in more sheltered areas (NOAA, 2003; Figures 3.17, 3.18). Tern Island in the atoll is the site of a U.S. Fish and Wildlife Service field station, which occupies à former U.S. Coast Guard (USCG) Long-Range Aids to Navigation (LORAN) station that closed in 1979. The lagoon is also unusual in that it contains one exposed volcanic pinnacle (La Perouse) representing the last vestiges of the high island from which the atoll was derived, as well as approximately nine low, sandy islets. The sand islets are small, shift position, and disappear and reappear.

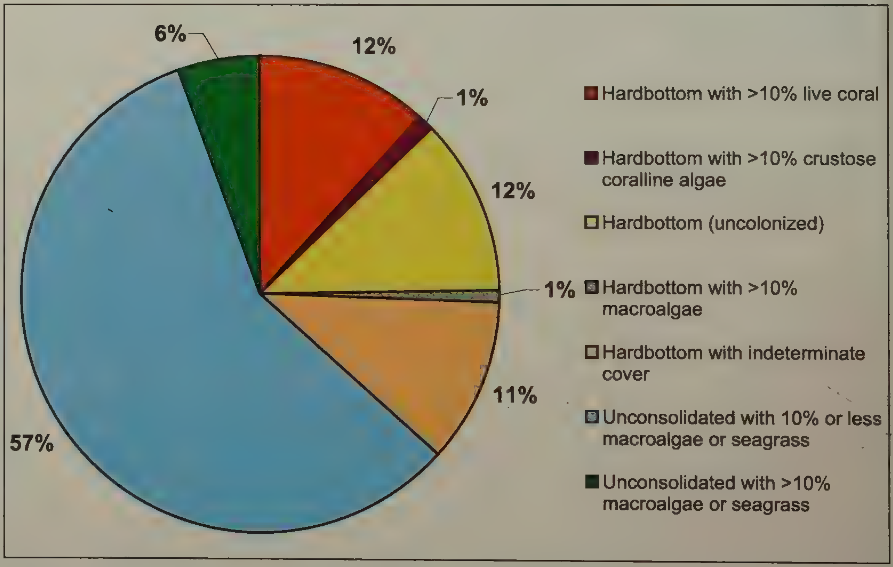


Figure 3.17. Percent composition of mapped benthic habitats at French Frigate Shoals based on NOAA benthic habitat maps. Source: NOAA 2003.

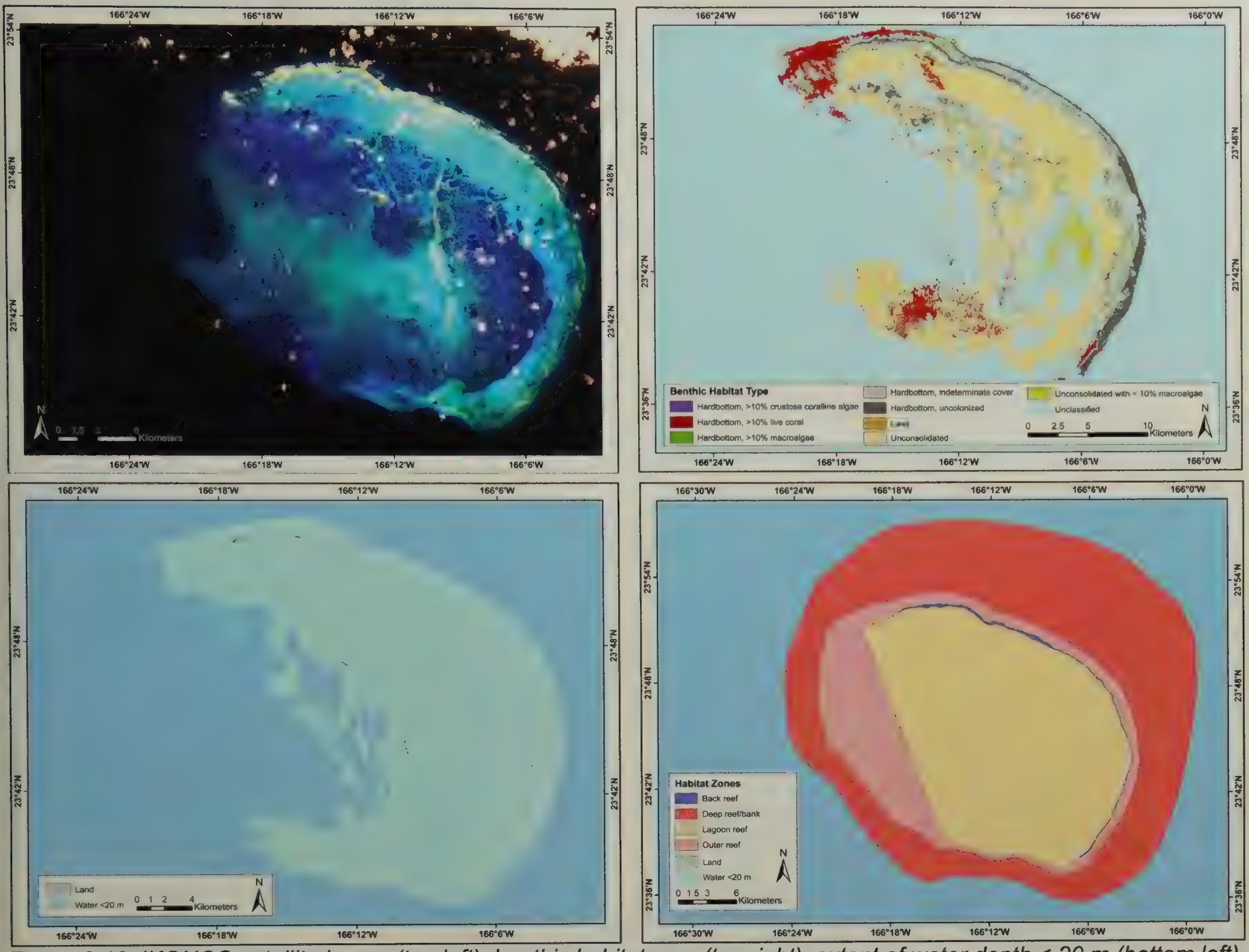


Figure 3.18. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for French Frigate Shoals. Maps: L. Wedding.

Table 3.8. Summary statistics for multibeam surveys conducted around French Frigate Shoals (2002-2008).

FRENCH FRIGATE SHOALS	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	681.15	-294.50	0.00	294.50	-42.15	50.69
	266 to 588	284.10	-620.51	-134.19	486.32	-400.26	100.79
	588 to 1,046	54.56	-699.90	-572.38	127.52	-638.08	33.01
Slope	9 to 226	-	0.00	70.49	70.49	2.40	4.33
	266 to 588	-	0.00	73.04	73.04	6.28	6.10
	588 to 1,046	-	0.00	62.14	62.14	6.84	5.45
Aspect	9 to 226	-	-1.00	360.00	361.00	150.34	115.05
	266 to 588	-	-1.00	360.00	361.00	171.14	127.29
	588 to 1,046	-	-1.00	359.99	360.99	235.36	79.11
Rugosity	9 to 226	-	1.00	3.25	2.25	1.01	0.03
	266 to 588	-	1.00	3.74	2.74	1.01	0.03
	588 to 1,046	-	1.00	2.29	1.29	1.02	0.04

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

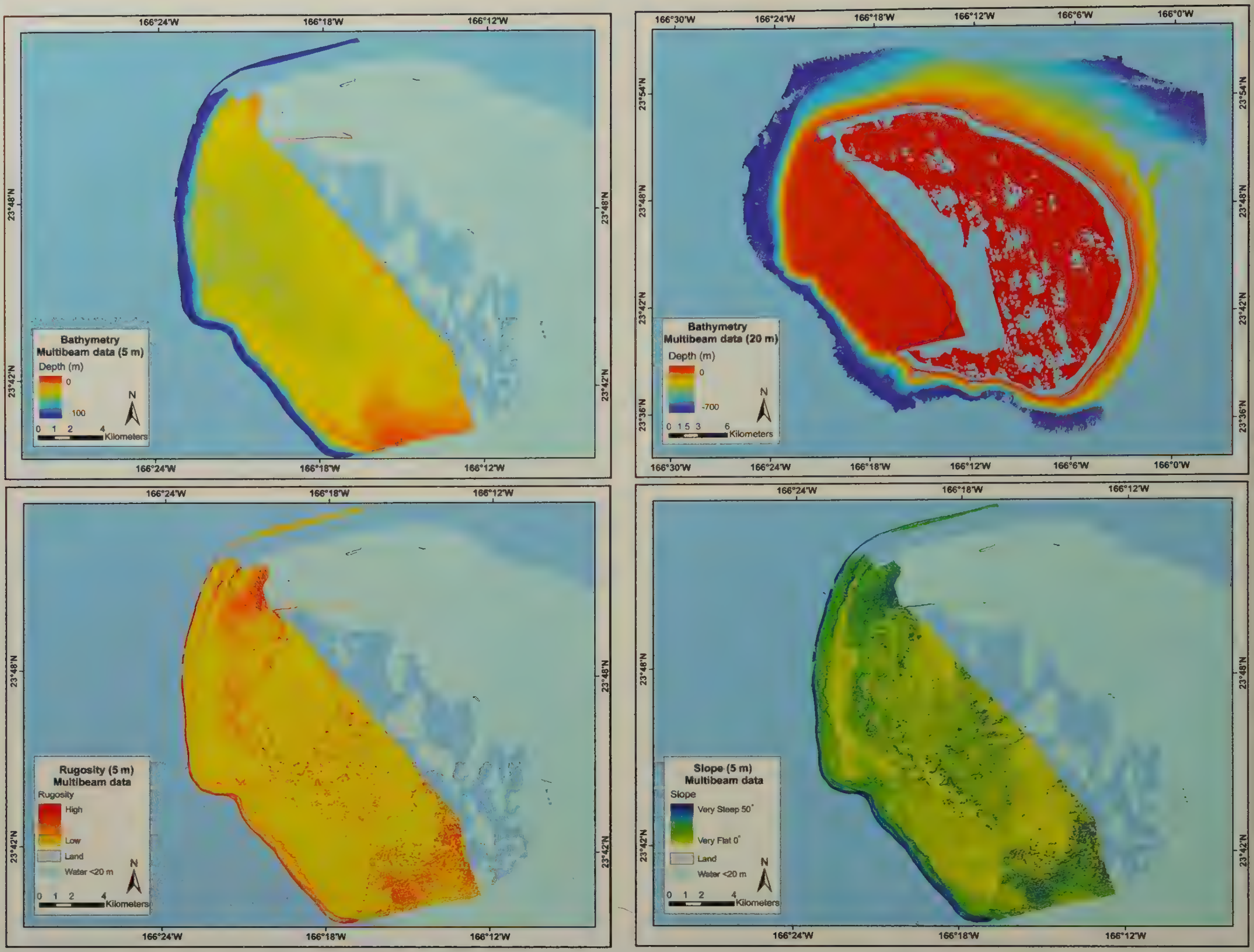


Figure 3.19. 5 m (top left) and 20 m bathymetry (top right), rugosity (5 m)(bottom left), and slope (5 m)(bottom right) for French Frigate Shoals. 20-m bathymetry plot includes derived depths from IKONOS imagery. Maps: L. Wedding.

Slope increases rapidly between the shallow and intermediate depth range (266-588 m) and then increases slightly between 588 and 1,046 m. Aspect ratio shows a gradual increase from shallow to deep depth bins while rugosity did not vary with depth (Table 3.8).

French Frigate Shoals is the first island for which a substrate type map has been produced. Using depth, backscatter, multibeam derivatives such as rugosity, slope, and variance (Figure 3.19), an unsupervised classification was performed to classify the substrate type into hard and soft bottom classes (Figure 3.20). Figures 3.21 through 3.24 shows information used in developing hard/soft and BPI maps. These products are designed to aid management agencies in developing sampling protocols that focus on hard (non-sand) substrates for coral benthic habitat studies and benthic habitat maps.

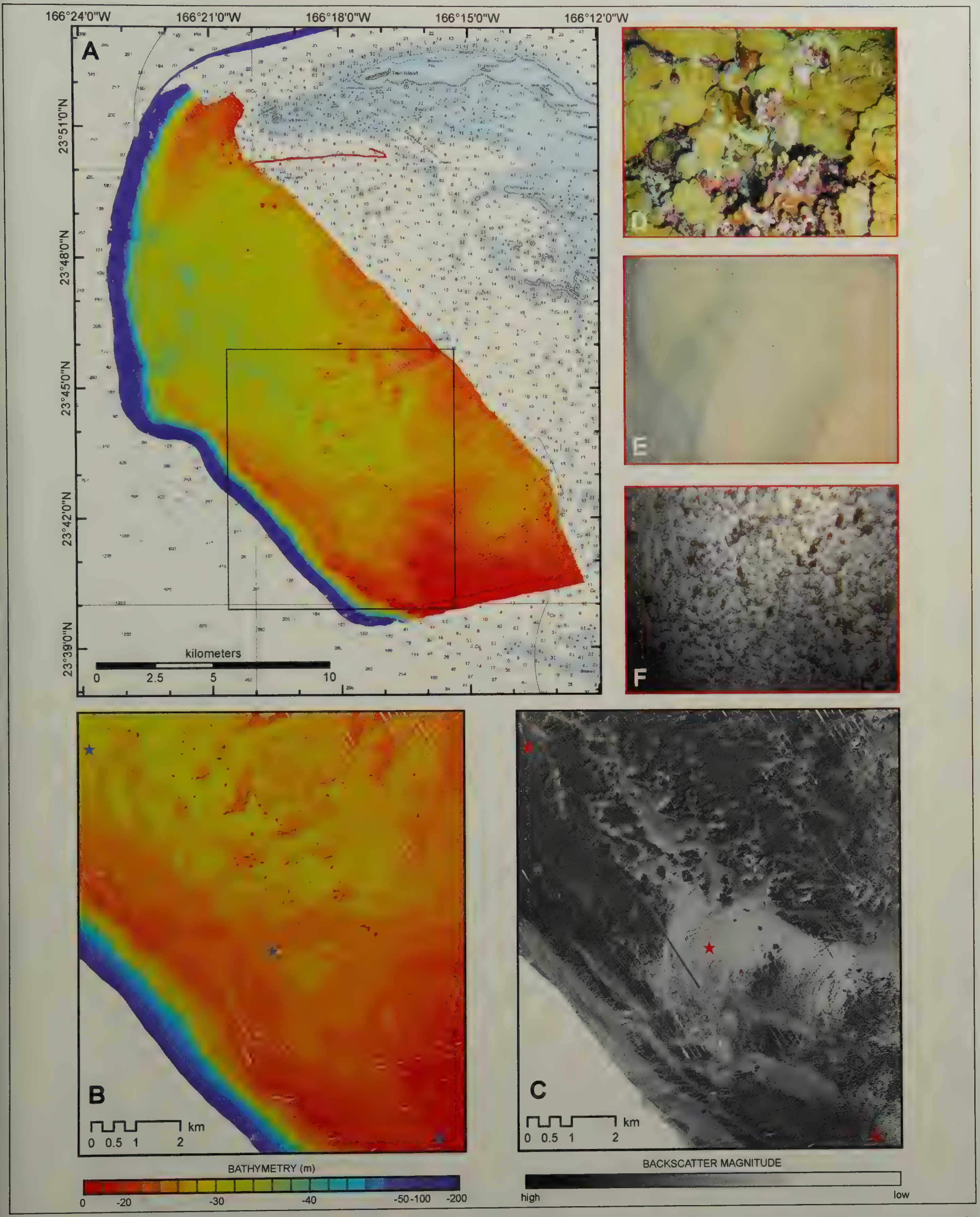


Figure 3.20. (A) Multibeam bathymetry data collected on the bank top at French Frigate Shoals. Black box corresponds to the location of the bathymetry (B) and backscatter (C) close-ups. Stars in (B) and (C) indicate the locations, from top to bottom (northwest to southeast), of the TOAD frame grabs shown in (D, E, and F). These data are used to create accurate habitat maps for moderate depth ecosystems in the NWHI using image processing techniques.

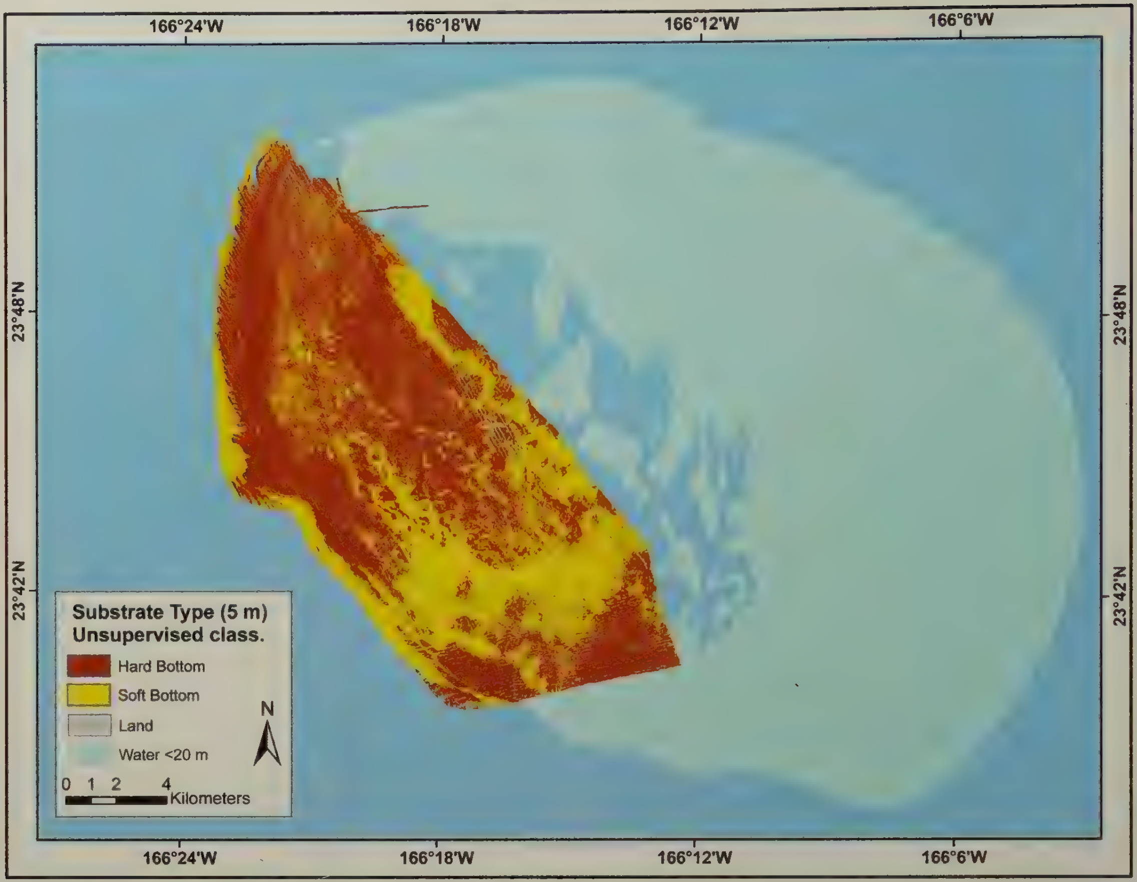


Figure 3.21. Hard/soft substrate type from French Frigate Shoals as produced by an unsupervised classification using ENVI.

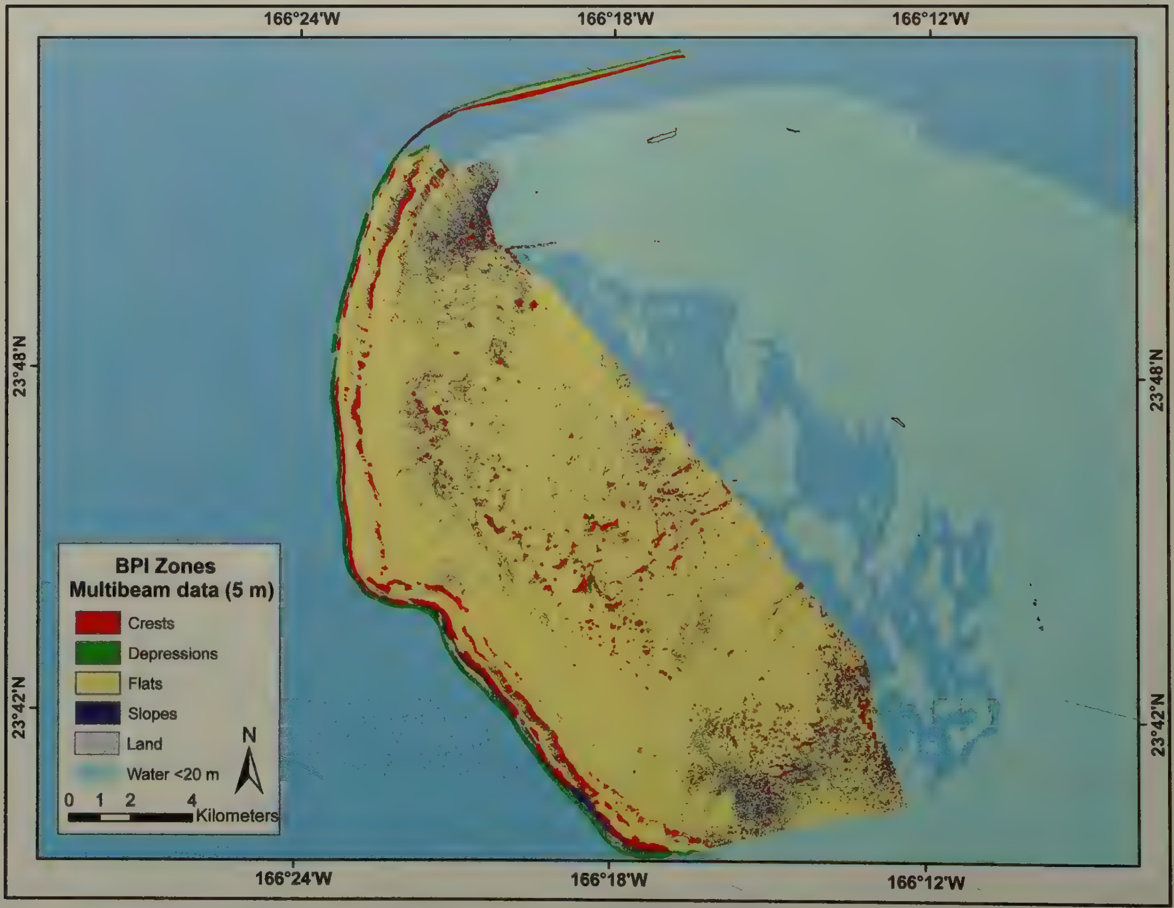


Figure 3.22. Bathymetric Position Index (BPI) zones for French Frigate Shoals. Source: Lundblad et al., 2006.

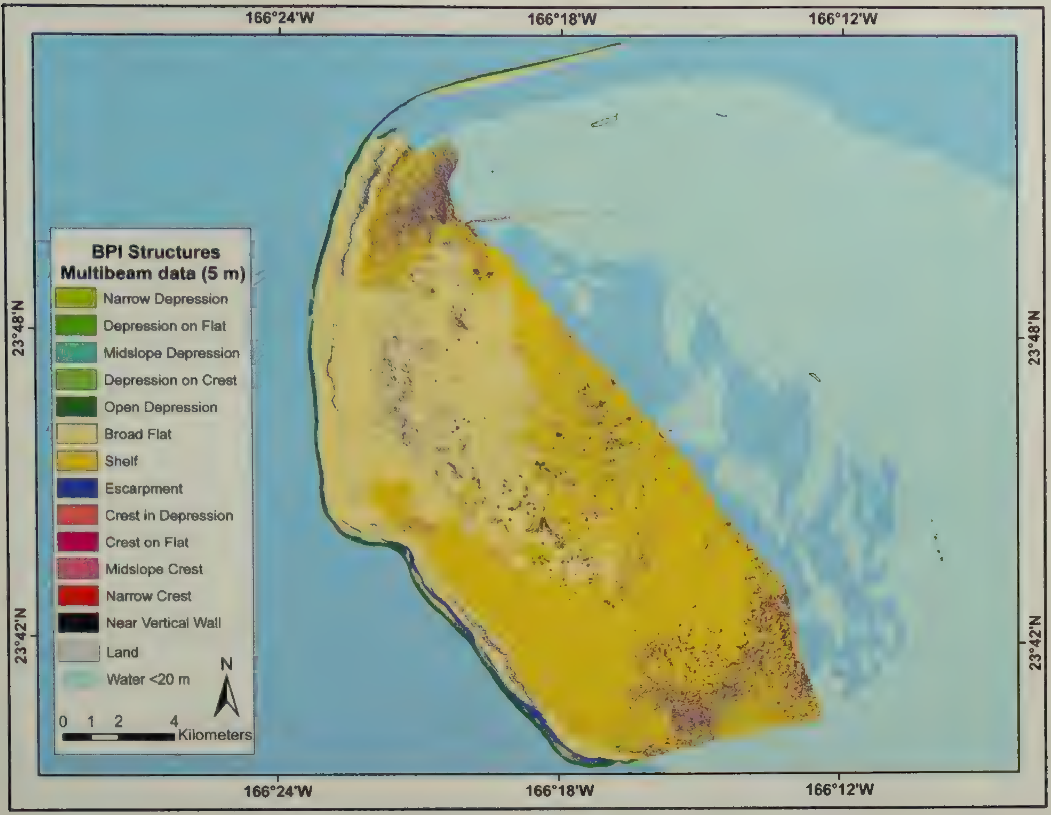


Figure 3.23. Bathymetric Position Index (BPI) structures for French Frigate Shoals. Source: Lundblad et al., 2006.

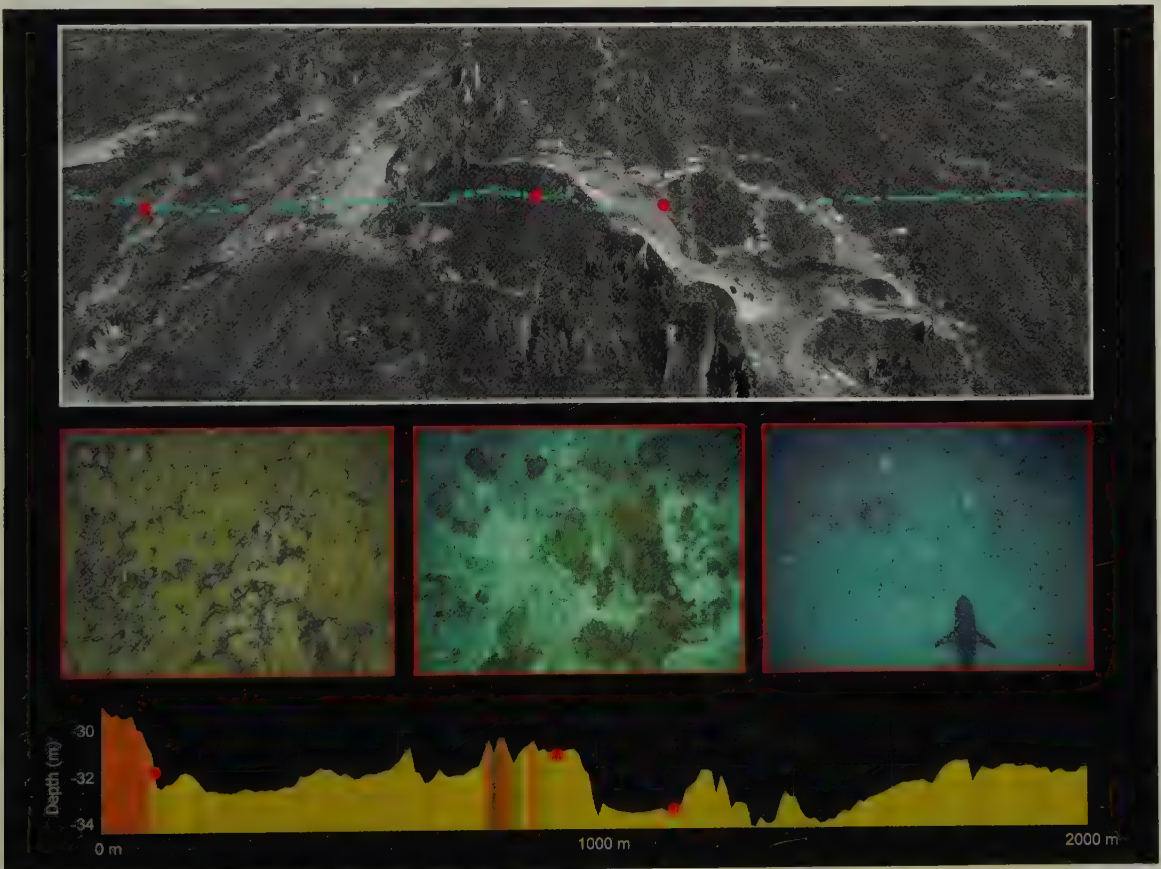
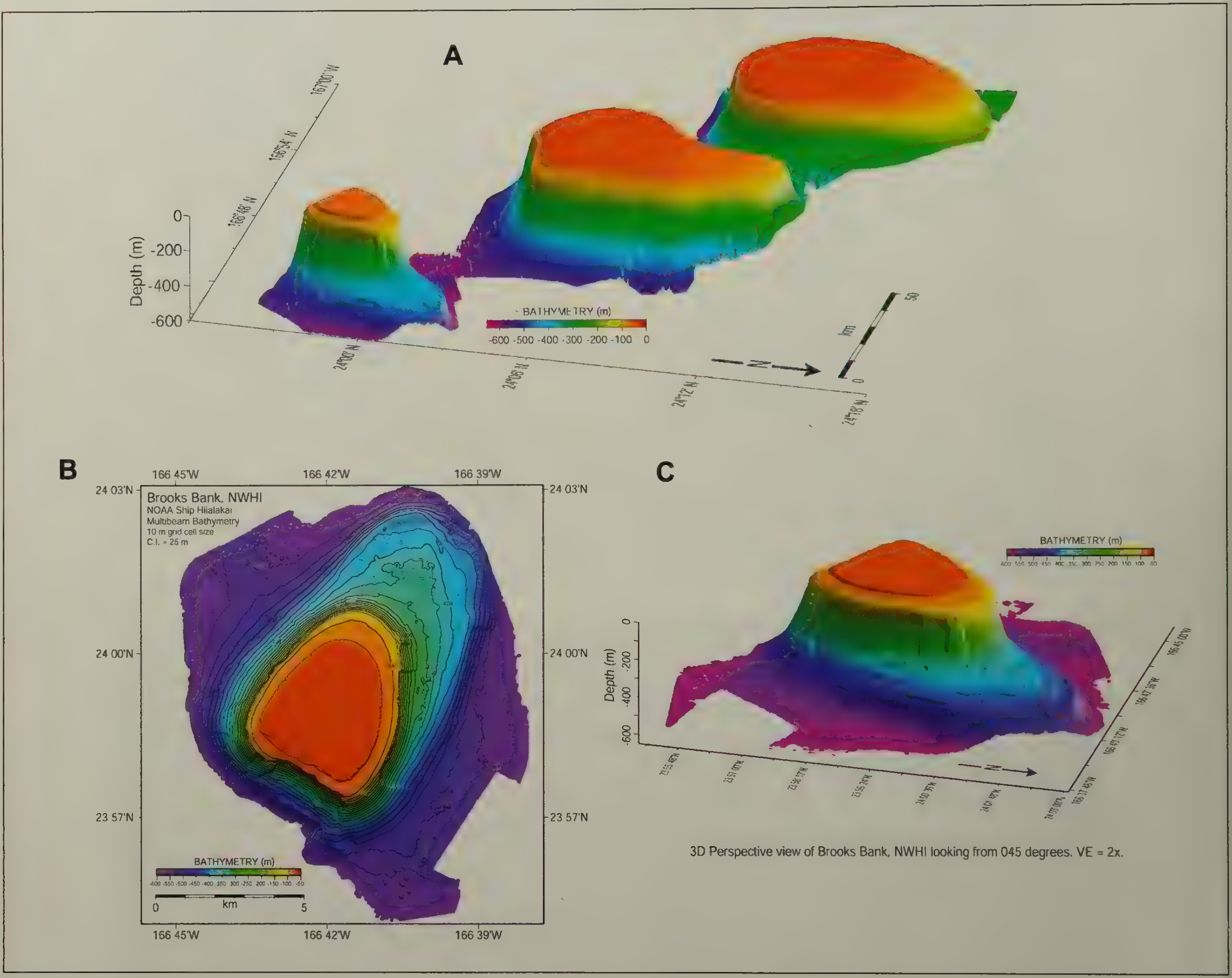


Figure 3.24. French Frigate Shoals backscatter (top) and optical data (center) used to develop hard soft maps. The bottom panel shows a profile of the terrain from concurrent bathymetric data. Red dots indicate location of three photographs. Dark areas in the backscatter indicate high intensity and can often be correlated to areas of coral cover, hard substrate, and elevated bathymetry (two left photos), while lighter areas can often be correlated with sandy, softer substrate and depressions.

Brooks and St. Rogatien Banks

The Brooks and St. Rogatien Banks include four submerged banks between French Frigate Shoals and Gardner Pinnacles (Figure 3.25). These four banks are guyots (flat-topped seamounts) and all have at least two different terraces near their summits that indicate previous sea level stands.



3D Perspective view of Brooks Bank, NWHI looking from 045 degrees. VE = 2x.

Figure 3.25. 3-D perspective of Brooks Banks. (A) Perspective view of the Brooks Banks looking from the northeast. The Brooks Banks exhibit a classic flat-topped morphology created by erosion when the banks were previously at or near sea-level. Multiple terraces around the bank edges are evidence for additional sea-level stands (B,C). Submarine canyons incise the steep bank edges and blocks of material at the base of the slopes are probably slumps or landslide deposits.

Gardner Pinnacles

Gardner Pinnacles consists of two emergent basaltic volcanic peaks estimated to be 15.8 million years in age (Clague 1996), which represent the oldest high islands in the Hawaiian chain. In scale, these pinnacles are small, the largest reaching only 54.8 m high and having a diameter of approximately 179.8 m. Due to their limited size, they support only a single species of land plant (*Portulaca lutea*) and a few terrestrial arthropod species, but they are by contrast excellent habitat for seabirds (Clapp, 1972). Guano from such seabirds gives the peaks a "frosted" appearance, indicating their importance as roosting and breeding sites for at least 12 subtropical species. These remnant volcanic pinnacles are surrounded by approximately 2,428 km^2 of coral reef habitat, most of which is in waters 18.3 m or deeper (Figure 3.26). The shallow water reef area within 10 fathoms covers less than one square kilometer (0.7 km^2) but the surrounding bank out to 100 fathoms covers 2,428 km^2. The relatively flat bank is in the 30 to 40 m depth range and consists of mostly sand and algal bottom with occasional rock outcroppings. The Pinnacles do not offer much protection from heavy waves and corals are more abundant on elevated surfaces and behind rises or mounds that are protected from wave action. The lack of shallow water environments limits the number of reef building species that can survive the conditions at the reefs and powerful wave action reduces the growth rate of corals (Grigg 1981), coralline algae and other reef-building organisms.

Multibeam data were collected in 2002 at Gardner Pinnacles on cruise KM0206 on the 25, 50 and/or 100-fm isobaths in order to delineate boundaries for the National Marine Sanctuaries program (Figure 3.27).

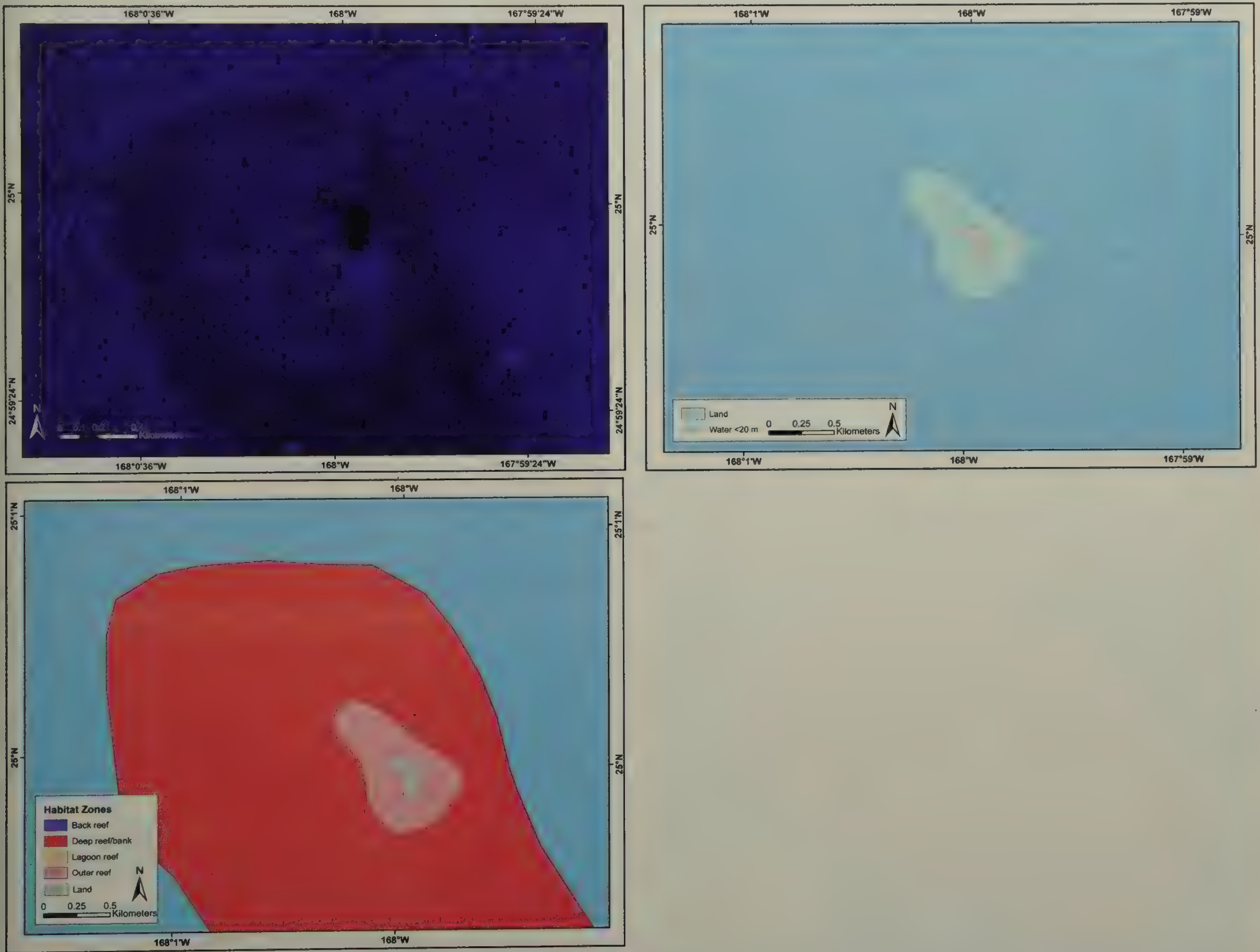


Figure 3.26. IKONOS satellite image (top left), extent of water depth <20 m (top right), and habitat zones (bottom left) for Gardner Pinnacles. Maps: L. Wedding.

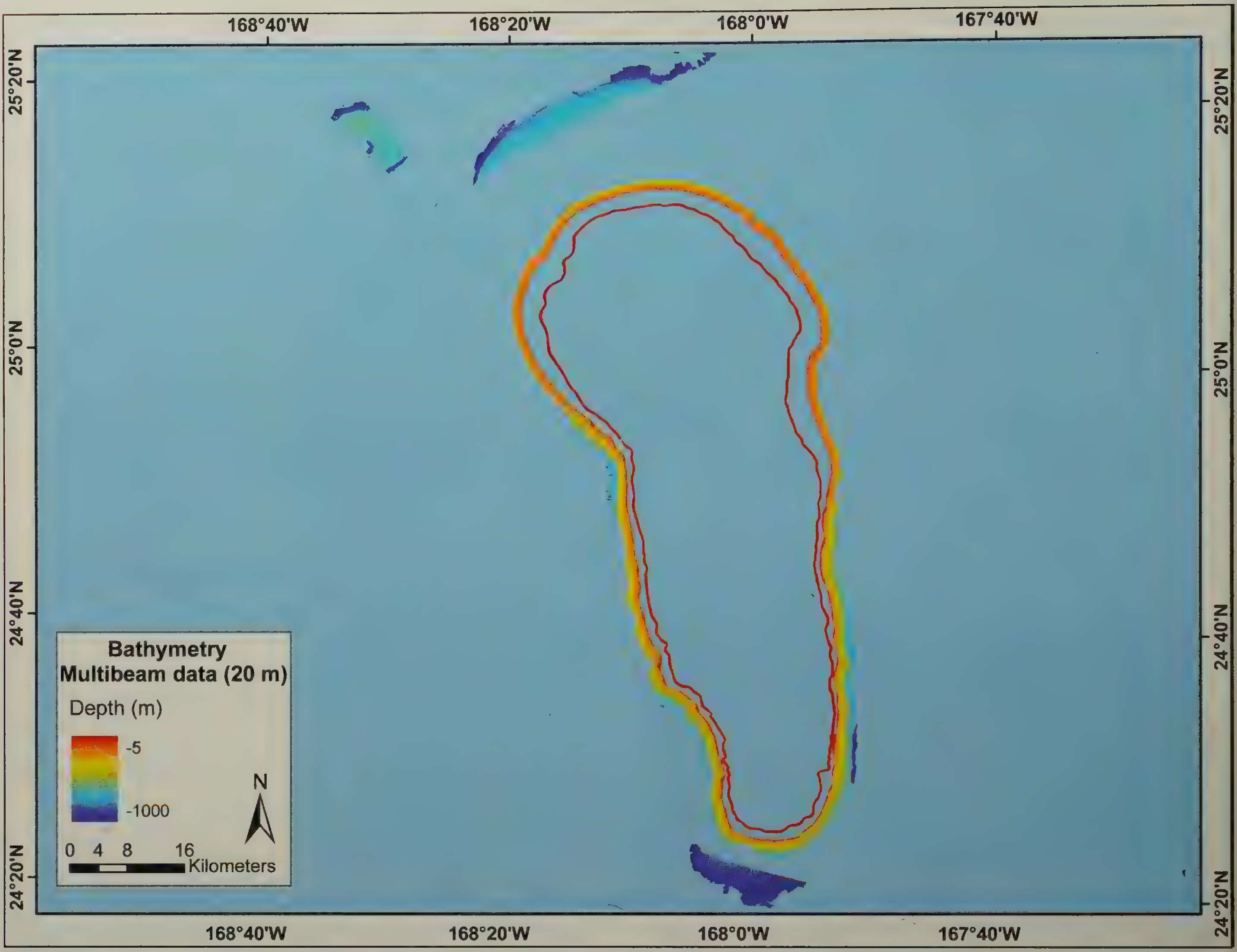


Figure 3.27. Gardner Pinnacles multibeam data collected in 2002 during KM0206.

Maro Reef

Maro Reef is a largely submerged open atoll 19.7 million years old (Clague, 1996). At very low tide, only a small coral rubble outcrop of a former island is believed to break above the surface; as a result, Maro supports no terrestrial biota. In contrast, the shallow water reef system is extensive, covering nearly 2,023 km², and is the largest coral reef in the Monument. Maro's reefs are intricate and reticulated, forming a complex network of reef crests, patch reefs, and lagoons. Deepwater channels with irregular bottoms cut between these shallow reef structures, but navigation through them is difficult and hazardous. Cover types range from unconsolidated with 10% or less macroalgae cover to areas with greater than 10% coral or crustose coralline algae (NOAA, 2003; Figures 3.28, 3.29).

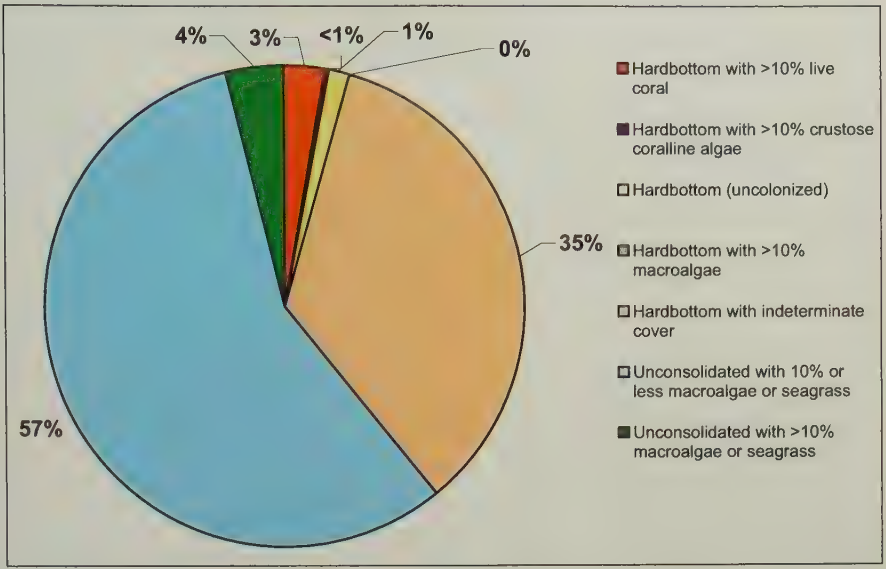


Figure 3.28. Percent composition of mapped benthic habitats at Maro Reef based on NOAA benthic habitat maps. Source: NOAA, 2003.

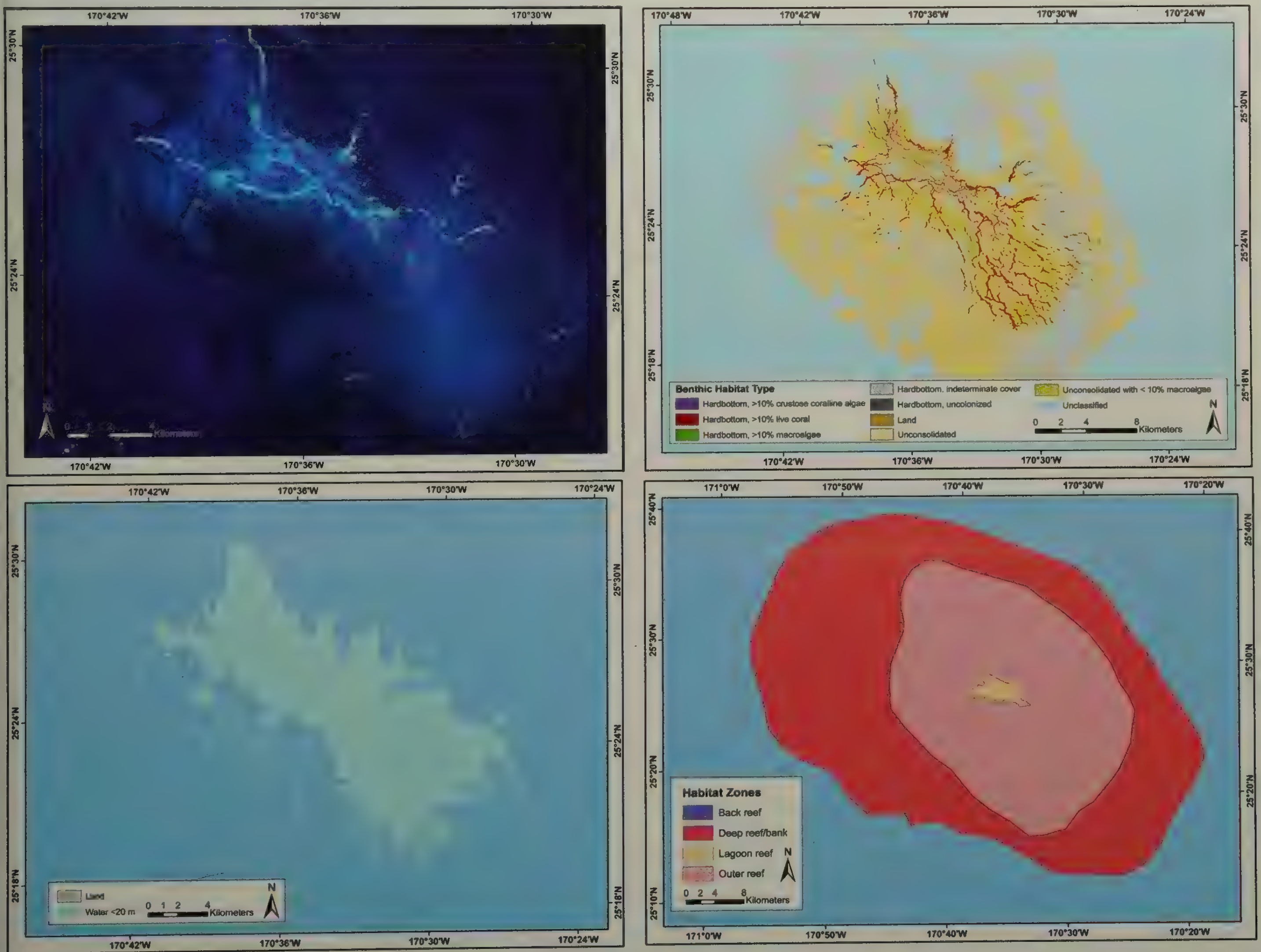


Figure 3.29. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Maro Reef. Maps: L. Wedding.

Because the outermost reefs absorb the majority of the energy from the open ocean swells, the innermost reticulated reefs and aggregated patch reefs are sheltered and have the characteristics of a true lagoon. Given the structural complexity of this platform, its shallow reefs are poorly charted and largely unexplored.

Multibeam surveys were conducted at Maro Reef in 2002 (KM0206) and 2005 (HI0508; Figure 3.30). The 2006 "ring" surveys on the perimeter were planned to delineate the 25-, 50-, and/or 100-fm isobaths for boundary designation purposes.

At Maro, slope increases greatly between the shallow (<226 m) and intermediate depths (226-588 m) and then declines slightly with greater depths (588-1,045 m). Aspect ratio declined slightly with depth from shallow to deep while rugosity was similar among all depths (Table 3.9).

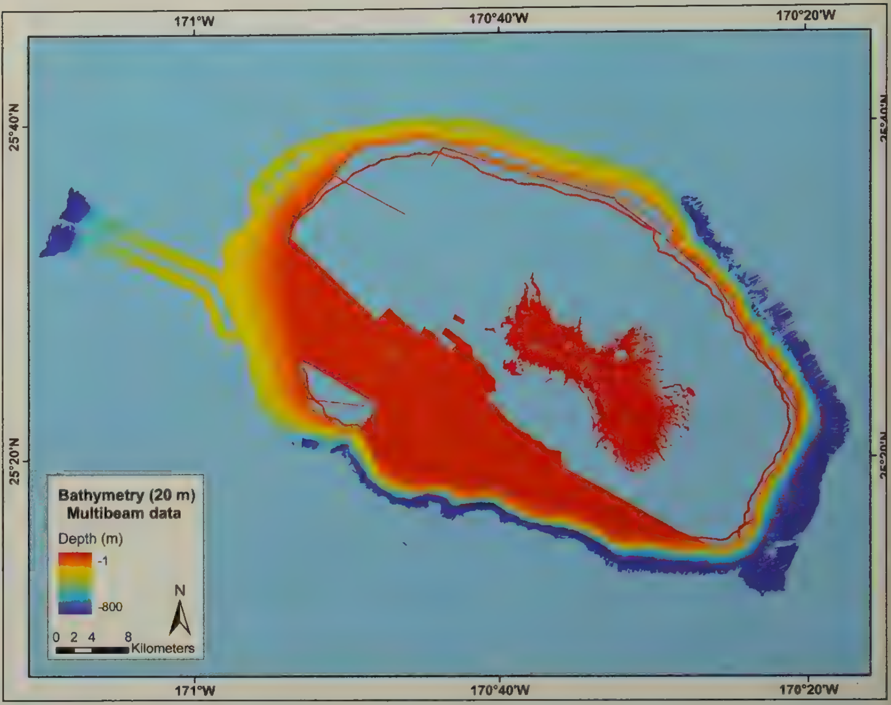


Figure 3.30. 20 m Multibeam bathymetric data collected at Maro Reef in 2002 and 2005 with derived depths from IKONOS imagery near island center. Map: L. Wedding.

Table 3.9. Summary statistics for multibeam surveys conducted around Maro Reef (2002-2006).

MARO	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	900.29	-259.40	-1.00	258.40	-65.03	56.96
	266 to 588	277.74	-616.72	-202.22	414.50	-356.19	106.15
	588 to 1,046	133.73	-800.00	-559.44	240.56	-689.07	61.27
Slope	9 to 226	-	0.00	62.67	62.67	2.47	4.30
	266 to 588	-	0.00	64.64	64.64	8.48	7.65
	588 to 1,046	-	0.00	55.35	55.35	7.82	5.76
Aspect	9 to 226	-	-1.00	360.00	361.00	184.40	108.58
	266 to 588	-	0.00	360.00	360.00	175.34	108.21
	588 to 1,046	-	-1.00	360.00	361.00	155.68	77.84
Rugosity	9 to 226	-	1.00	2.23	1.23	1.00	0.03
	266 to 588	-	1.00	2.43	1.43	1.02	0.04
	588 to 1,046	-	1.00	2.08	1.08	1.02	0.04

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

Laysan

Laysan is a formed atoll, estimated to be 20.7 million years old (Clague, 1996), with a maximum elevation of approximately 15 m above sea level. By land area it is the second largest island in the Monument, with a land area of approximately 3.7 km², surrounded by close to 405 km² of coral reef. Most of the reef area at Laysan lies in deeper waters, with a small, shallow water reef area in a bay off the southwest side of the island. It is well vegetated (except for its sand dunes) and contains a hyper-saline lake, which is one of only five natural lakes in the state of Hawaii. Laysan's coral reef habitat totals approximately 26.5 km² within 10 fathoms and 584.5 km² out to 100 fathoms (Figures 3.31, 3.32). The fringing reef surrounding the island varies from 100 to 500 m in width and is most extensive at the northwest end of the island. Inside the

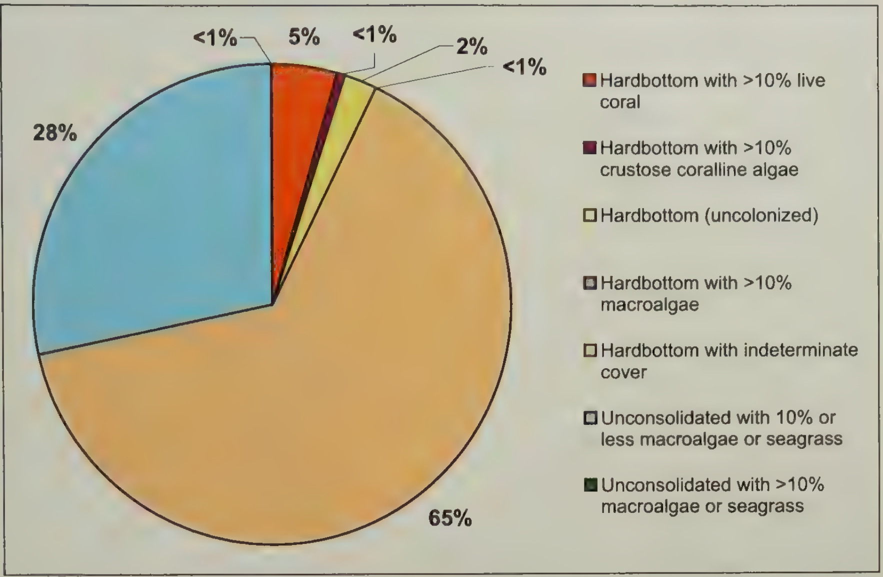


Figure 3.31. Percent composition of mapped benthic habitats at Laysan Island based on NOAA benthic habitat maps. Source: NOAA, 2003.

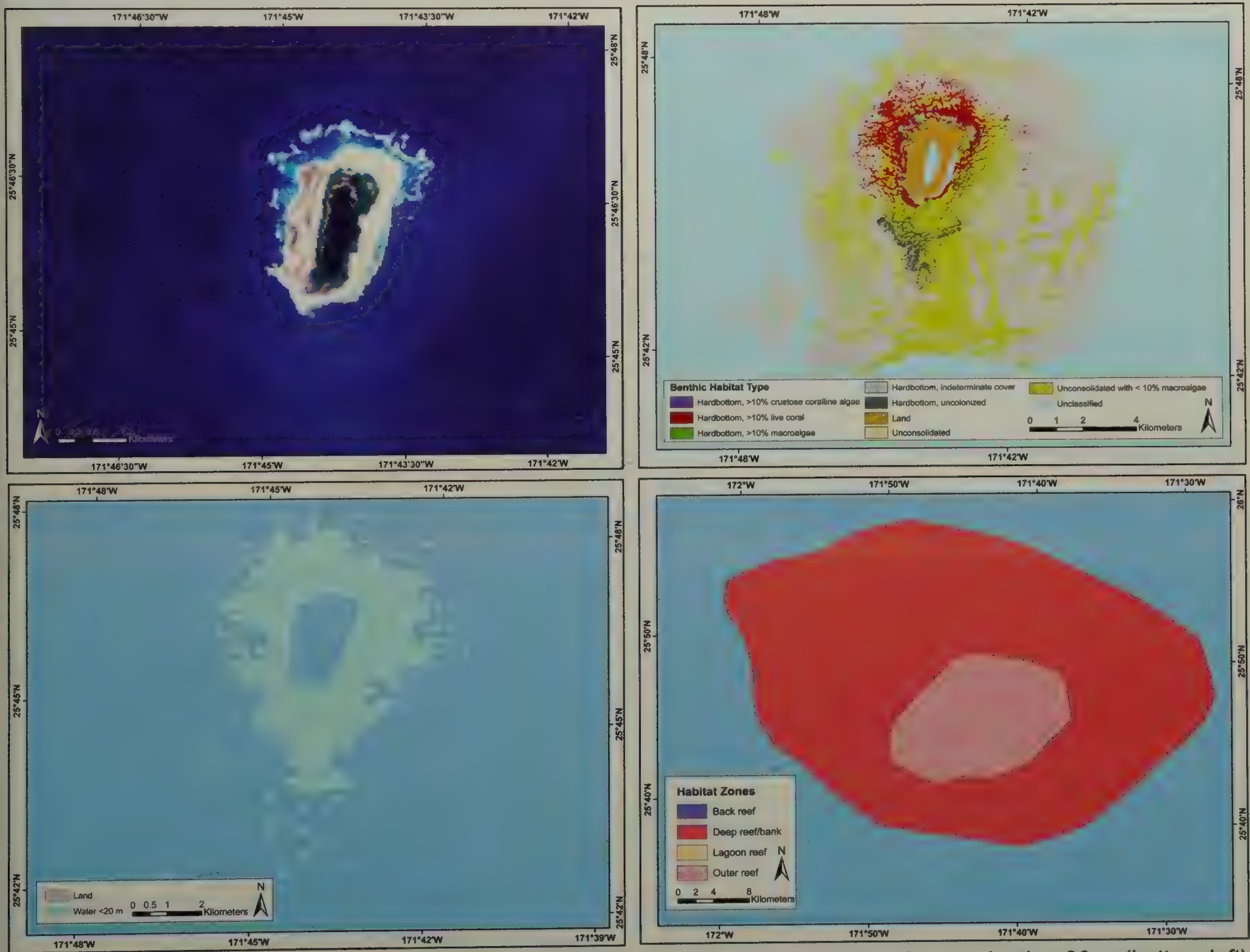


Figure 3.32. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Laysan Island. Maps: L. Wedding.

reef is a narrow, shallow channel which nearly encircles the island except for the south and southeast sides. Deeper reef habitats are mostly robust spur-and-grooves around most of the island and a heavily eroded northern section with numerous caves, overhangs and large holes on a sloping reef with small sand channels. The base of these reefs and the spur-and-grooves ended in broad sand flats with numerous small overhangs and holes. Despite lacking much protection from the detrimental effects of waves, Laysan supports a surprisingly rich coral environment with good development along its leeward coasts. The small back reef, pass and moat near the island's western boat landing also help to diversify habitats and the number of coral species inhabiting them.

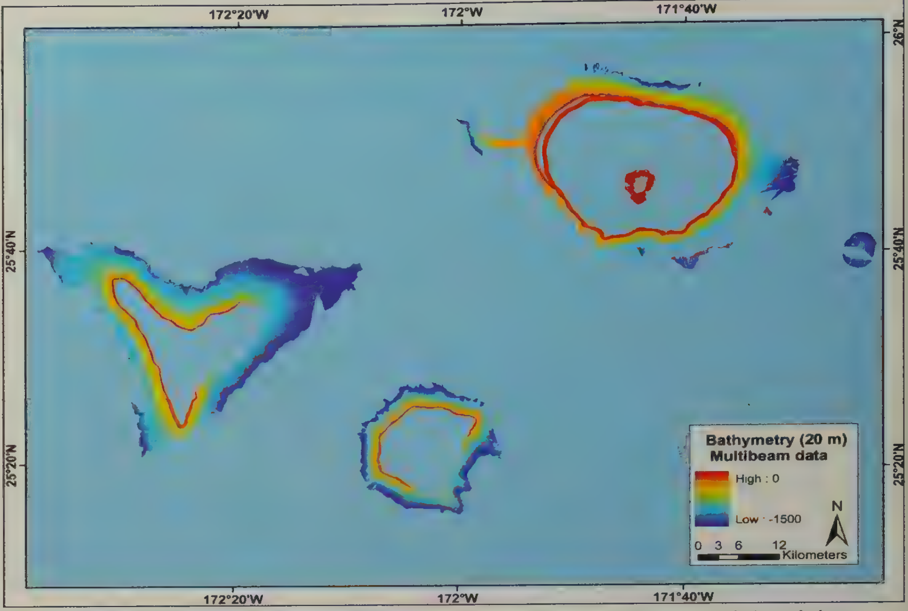


Figure 3.33. 20-m multibeam data collected around Laysan Island (upper right) and Northampton Seamounts (lower left). Derived depths from IKONOS imagery are shown around Laysan Island. Map: L. Wedding.

Multibeam surveys were conducted in 2002 during KM0206 in order to delineate 25, 50 and/or 100-fm boundaries around Laysan Island (Figure 3.33).

Lisianski-Neva Shoal

Lisianski Island (Papaapoho) is another raised atoll, rising to 12.1 m above sea level, and with approximately 1.6 km² of emergent land is the third largest island within the Monument. This 23.4-million-year-old island (Clague, 1996) is over 1.9 km across, consisting of an elevated rim surrounding a broad central depression, although unlike Laysan it does not enclose an interior saline lake. The coral cover on the platform around the island, called Neva Shoal, is extensive, totaling over 1,174 km² (Figures 3.34, 3.35).

Papaapoho describes a flat area with a depression or hollow, which is exactly how the island is shaped. Its highest point is a 12.2 m-high sand dune, and its lowest point is a depression to the south that runs as a channel toward the ocean.

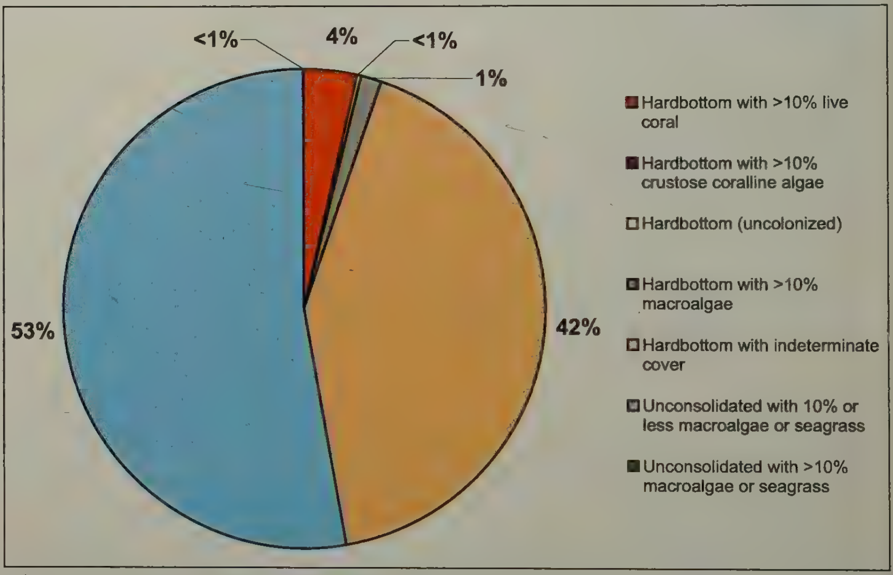


Figure 3.34. Percent composition of mapped benthic habitats at Lisianski-Neva Shoals based on NOAA benthic habitat maps. Source: NOAA, 2003.

Multibeam surveys were conducted in 2002 during KM0206 (Figure 3.36) in order to delineate 25, 50 and/or 100-fm boundaries around Lisianski Island and Neva Shoals. The slope increases dramatically between the shallow (<226 m) and the intermediate depth range (226-588 m) before it declines slightly in the deeper depth bin (588-1,045 m). Aspect ratio is highest in the deep and shallow depth ranges while the intermediate depth ranges (266-588 m) had the lowest aspect ratio. Rugosity increased sharply between shallow and intermediate depths with a slight decrease in the deepest depth bin (Table 3.10).

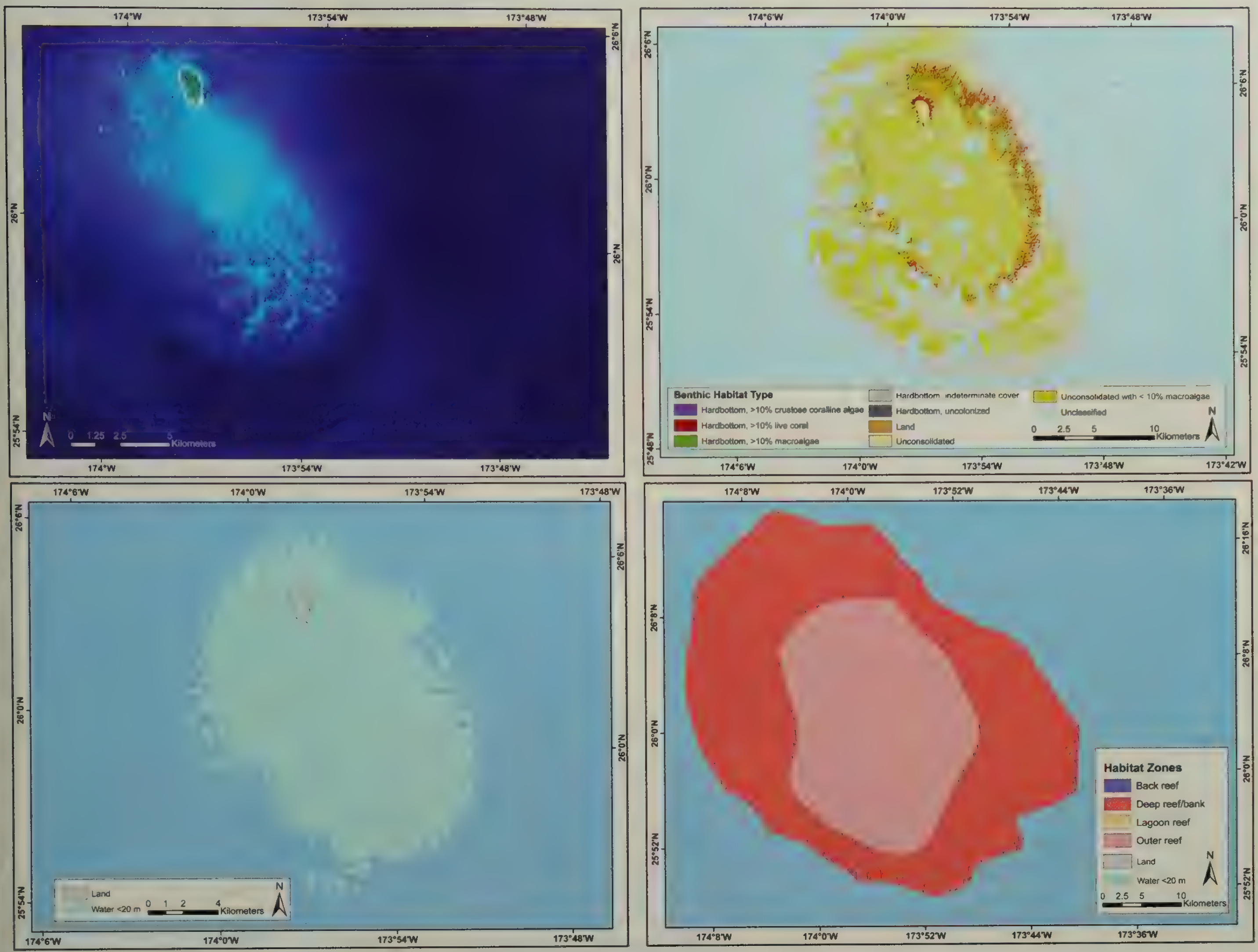


Figure 3.35. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Lisianski-Neva Shoals. Maps: L. Wedding.

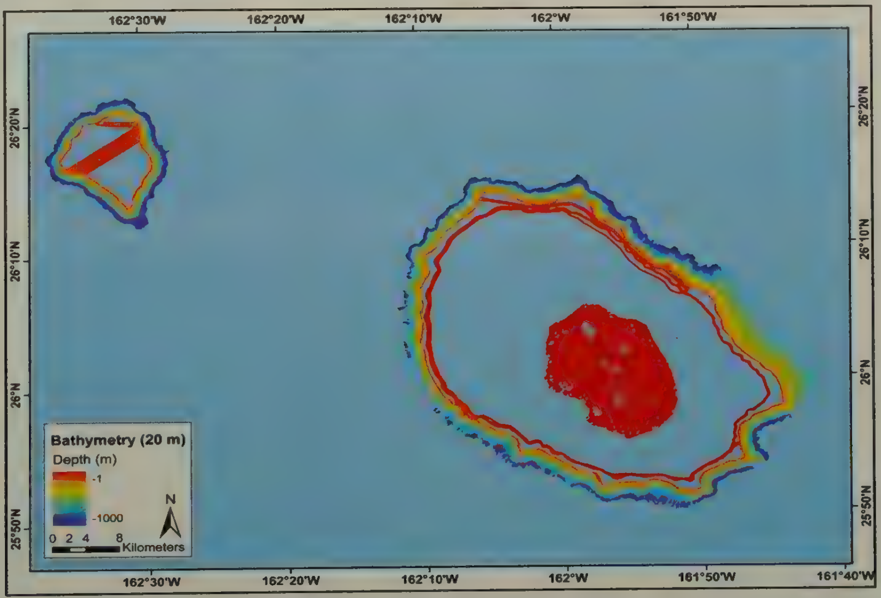


Figure 3.36. 20 m multibeam data collected around Lisianski-Neva Shoal in 2002 with derived depths from IKONOS imagery near island center. Map: L. Wedding.

Table 3.10. Summary statistics for multibeam surveys conducted around Lisianki (2002).

LISIANKI	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	367.36	-366.03	-1.00	365.03	-47.61	51.89
	266 to 588	166.36	-683.59	-159.95	523.64	-430.03	102.21
	588 to 1,046	194.73	-999.99	-511.34	488.65	-785.34	119.57
Slope	9 to 226	-	0.00	78.38	78.38	4.34	8.52
	266 to 588	-	0.00	81.39	81.39	21.19	12.56
	588 to 1,046	-	0.00	72.36	72.36	19.10	8.47
Aspect	9 to 226	-	-1.00	360.00	361.00	174.50	105.29
	266 to 588	-	-1.00	360.00	361.00	149.92	103.05
	588 to 1,046	-	-1.00	360.00	361.00	177.09	105.33
Rugosity	9 to 226	-	1.00	6.83	5.83	1.02	0.08
	266 to 588	-	1.00	6.89	5.89	1.12	0.19
	588 to 1,046	-	1.00	3.39	2.39	1.08	0.08

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

Pearl and Hermes

The name Holoikauaua celebrates the Hawaiian monk seals that haul out and rest here. Pearl and Hermes Atoll is a large atoll with several small islets, forming 0.38 km² of land surrounded by over 1,214 km² of coral reef habitat (Figures 3.37, 3.38). The atoll has an estimated age of 26.8 million years (Clague, 1996) and is over 32 km across and 19.3 km wide, with dunes rising above sea level. Unlike Lisianski and Laysan to the southeast, Pearl and Hermes Atoll is a true atoll, fringed with shoals, permanent emergent islands, and ephemeral sandy islets. These features provide vital dry land for monk seals, green turtles, and a multitude of seabirds, with 16 species breeding here. The islets are periodically washed over when winter storms pass through the area.

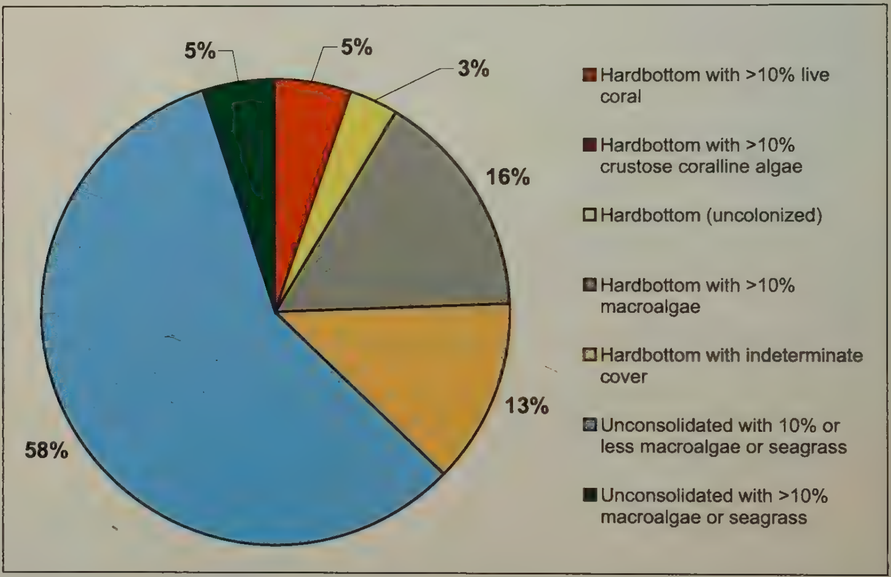


Figure 3.37. Percent composition of mapped benthic habitats at Pearl and Hermes Atoll based on NOAA benthic habitat maps. Source: NOAA, 2003.

Multibeam data were collected at Pearl and Hermes Atoll in 2005 (HI0509) to delineate the 25-, 50- and/or 100-fm boundaries and in 2006 to complete as much mapping of the atoll as possible (Table 3.11; Figure 3.39). Depths surveyed ranged from 9 m down to over 3,000 m. Slope increased by more than eight fold between the shallowest (9-226 m) and the next deepest (226-588 m) depth ranges. The slope declined slightly in the deepest depth bin (1,649-3,071 m). Aspect ratio increased steadily with increasing depth, while rugosity rose sharply between shallow (<226 m) and intermediate ranges (226-1,046 m) and then declined slightly in the deepest depth bin (Table 3.11). Figure 3.40 shows a guyot approximately 25 km southeast of Pearl and Hermes Atoll where monk seals have been reported to forage through satellite tracking.

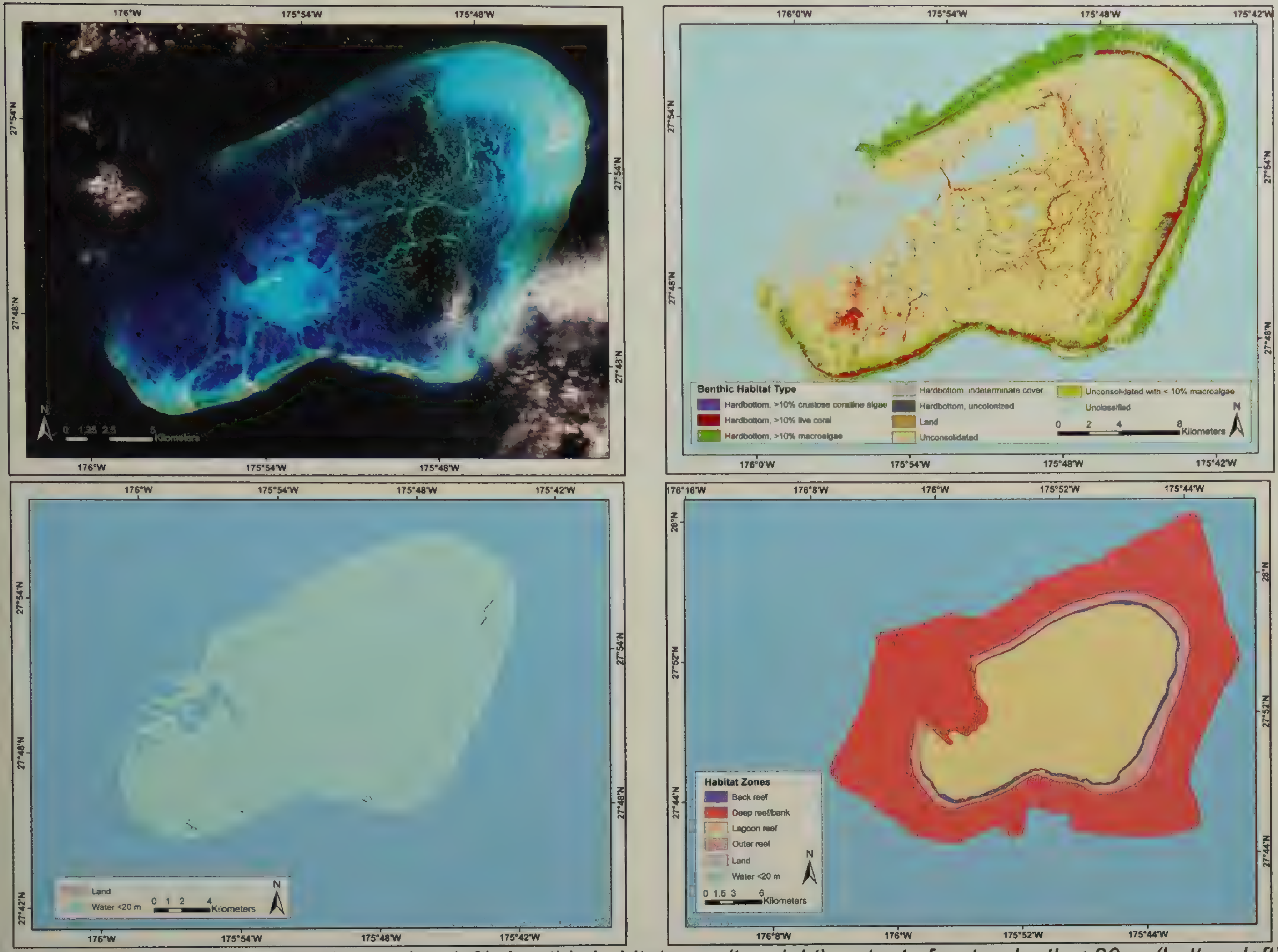


Figure 3.38. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Pearl and Hermes Atoll. Maps: L. Wedding.

Table 3.11. Summary statistics for multibeam surveys conducted around Pearl and Hermes (2005).

PEARL AND HERMES	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	611.14	-1,818.20	0.00	1,818.20	-44.22	48.84
	266 to 588	20.70	-876.60	-10.60	866.00	-336.52	103.37
	588 to 1,046	34.20	-1,169.10	-262.60	906.50	-862.04	123.81
	1,046 to 1,649	92.48	-1,858.90	-631.80	1,227.10	-1,368.91	175.49
	1,649 to 3,071	86.96	-3,071.30	-40.70	3,030.60	-1,979.21	281.68
Slope	9 to 226	-	0.00	77.41	77.41	3.39	4.73
	266 to 588	-	0.00	82.89	82.89	28.25	11.14
	588 to 1,046	-	0.00	84.42	84.42	28.60	11.14
	1,046 to 1,649	-	0.00	84.72	84.72	22.32	10.32
	1,649 to 3,071	-	0.00	87.49	87.49	15.04	9.89
Aspect	9 to 226	-	-1.00	360.00	361.00	158.44	116.76
	266 to 588	-	-1.00	359.94	360.94	198.48	97.80
	588 to 1,046	-	-1.00	360.00	361.00	202.81	95.63
	1,046 to 1,649	-	-1.00	360.00	361.00	224.08	98.92
	1,649 to 3,071	-	-1.00	360.00	361.00	225.85	98.48
Rugosity	9 to 226	-	1.00	14.14	13.14	1.01	0.03
	266 to 588	-	1.00	12.93	11.93	1.30	0.43
	588 to 1,046	-	1.00	18.72	17.72	1.32	0.48
	1,046 to 1,649	-	1.00	19.01	18.01	1.25	0.38
	1,649 to 3,071	-	1.00	89.27	88.27	1.16	0.46

***NOTE:** minimum = minimum value of a given metric within a universal depth class; maximum = the maximum value of a given metric within a universal depth class.

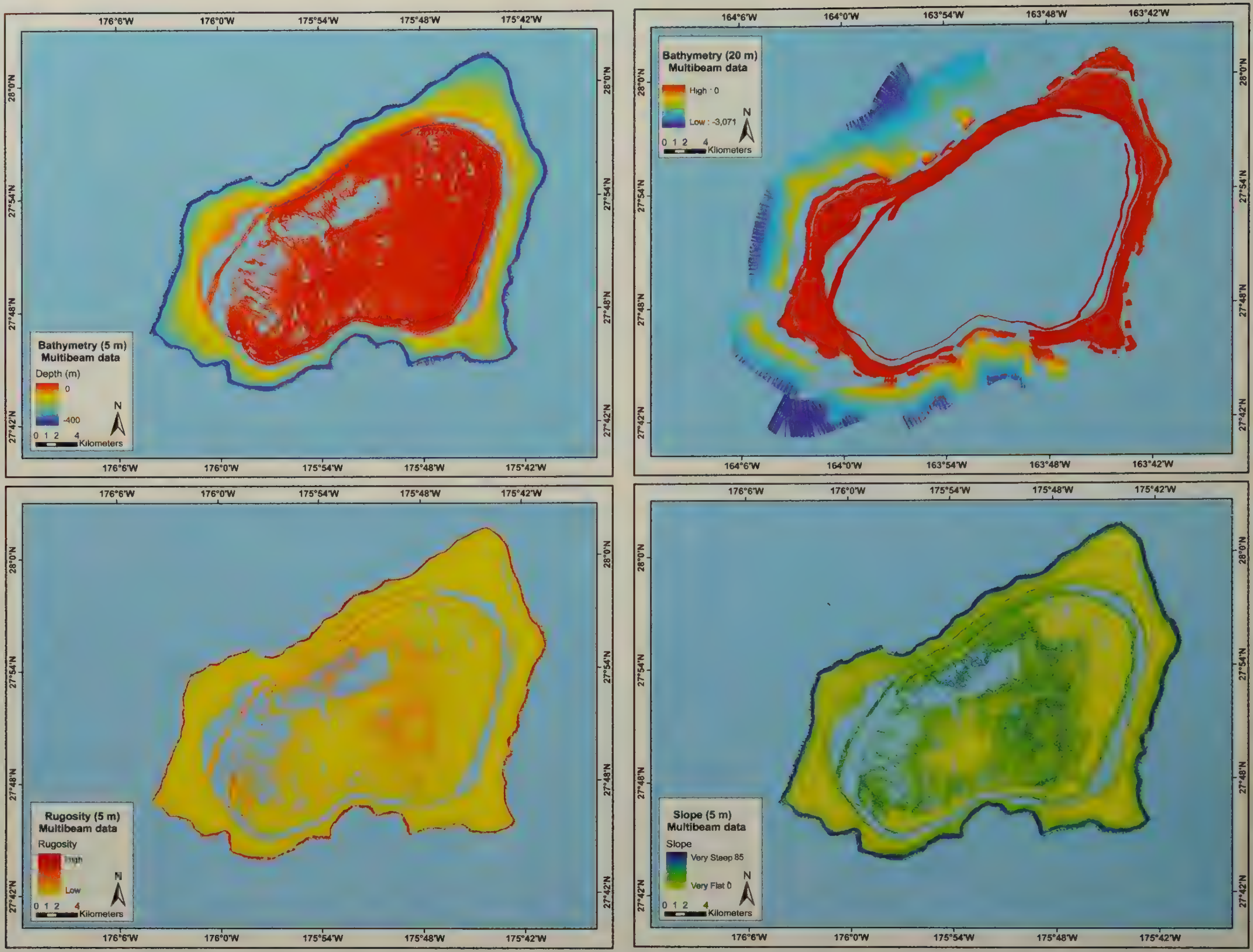


Figure 3.39. 5 m and 20 m bathymetry, rugosity (5 m), and slope (5 m) for Pearl and Hermes with derived depths from IKONOS imagery near island center. Maps: L. Wedding.

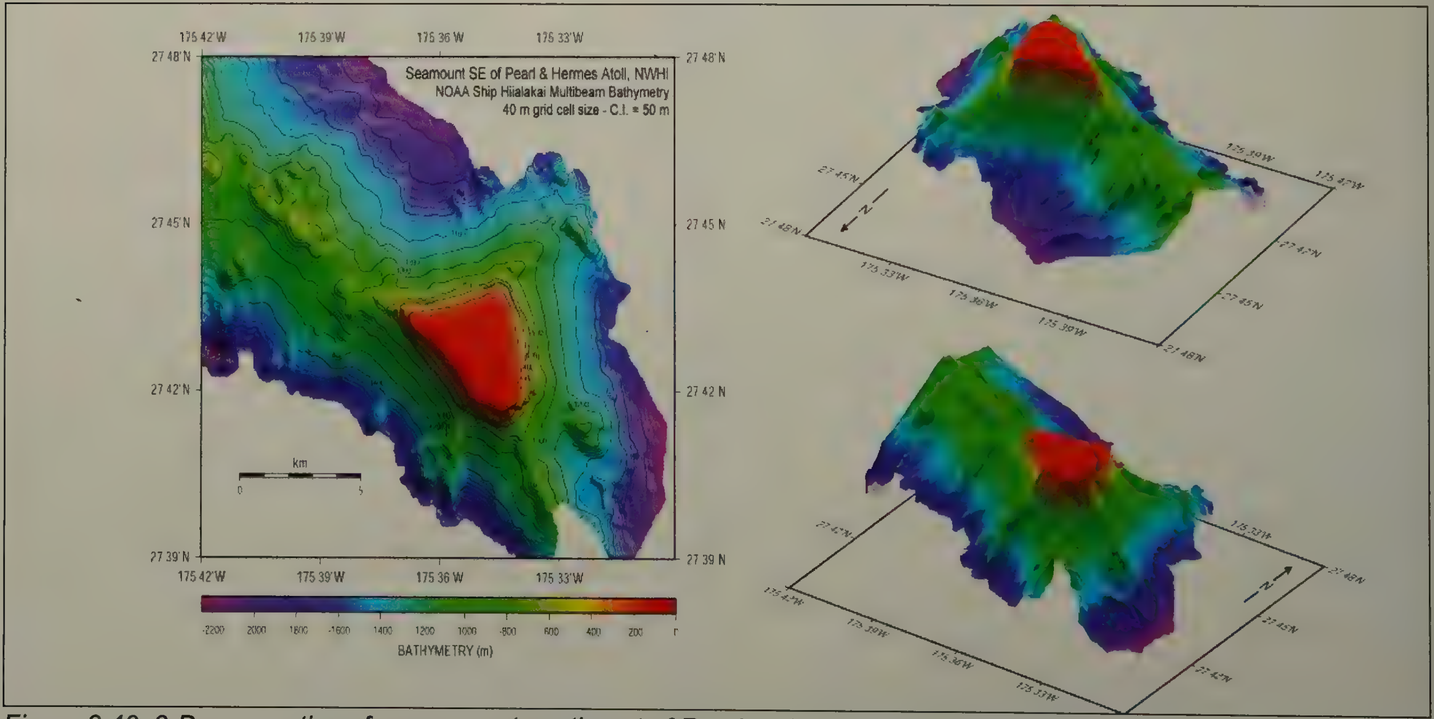


Figure 3.40. 3-D perspective of a seamount southeast of Pearl and Hermes Atoll. V.E. = 2x.

Midway Atoll

Midway Atoll consists of three sandy islets: Sand, 4.56 km^2; Eastern, 1.36 km^2; and Spit, 0.05 km^2 for a total of 1,464 5.9 km^2 in terrestrial area, lying within a large, elliptical barrier reef measuring approximately 8 km in diameter. The atoll, which is 28.7 million years old (Clague, 1996), is surrounded by more than 356 km^2 of coral reefs (Figures 3.41, 3.42). In 1965, the U.S. Geological Survey took core samples and hit solid basaltic rock 54.8 m beneath Sand Island and 377.9 m beneath the northern reef. Numerous patch reefs dot the sandy-bottomed lagoon. The atoll and surrounding seas were also the site of a pivotal battle of World War II, and Midway was an active Navy installation during the Cold War.

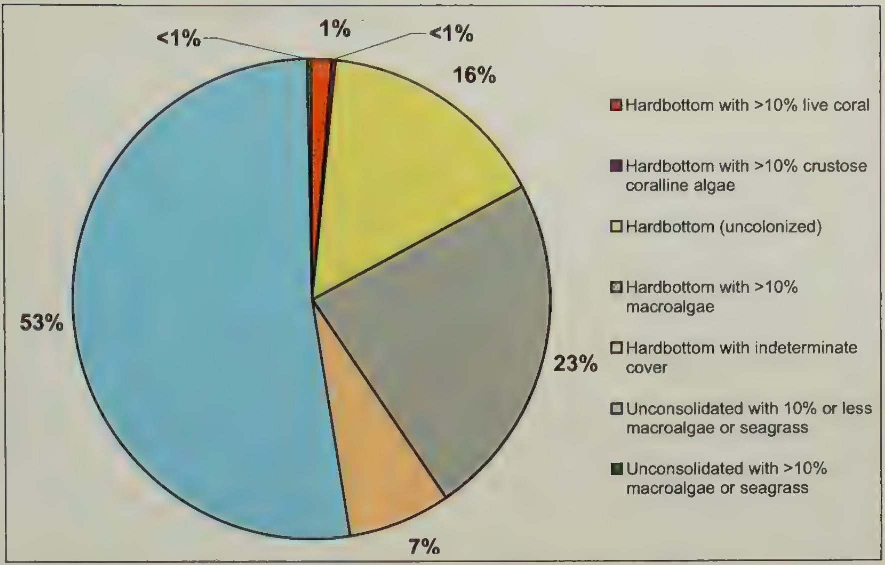


Figure 3.41. Percent composition of mapped benthic habitats at Midway Atoll based on NOAA benthic habitat maps. Source: NOAA, 2003.

Multibeam mapping surveys at Midway were conducted in 2003 (AHI0306) to delineate 25-, 50- and 100-fm boundaries and in 2005 (HI0503) and 2006 (HI0609) to add to coverage around the island for benthic habitat

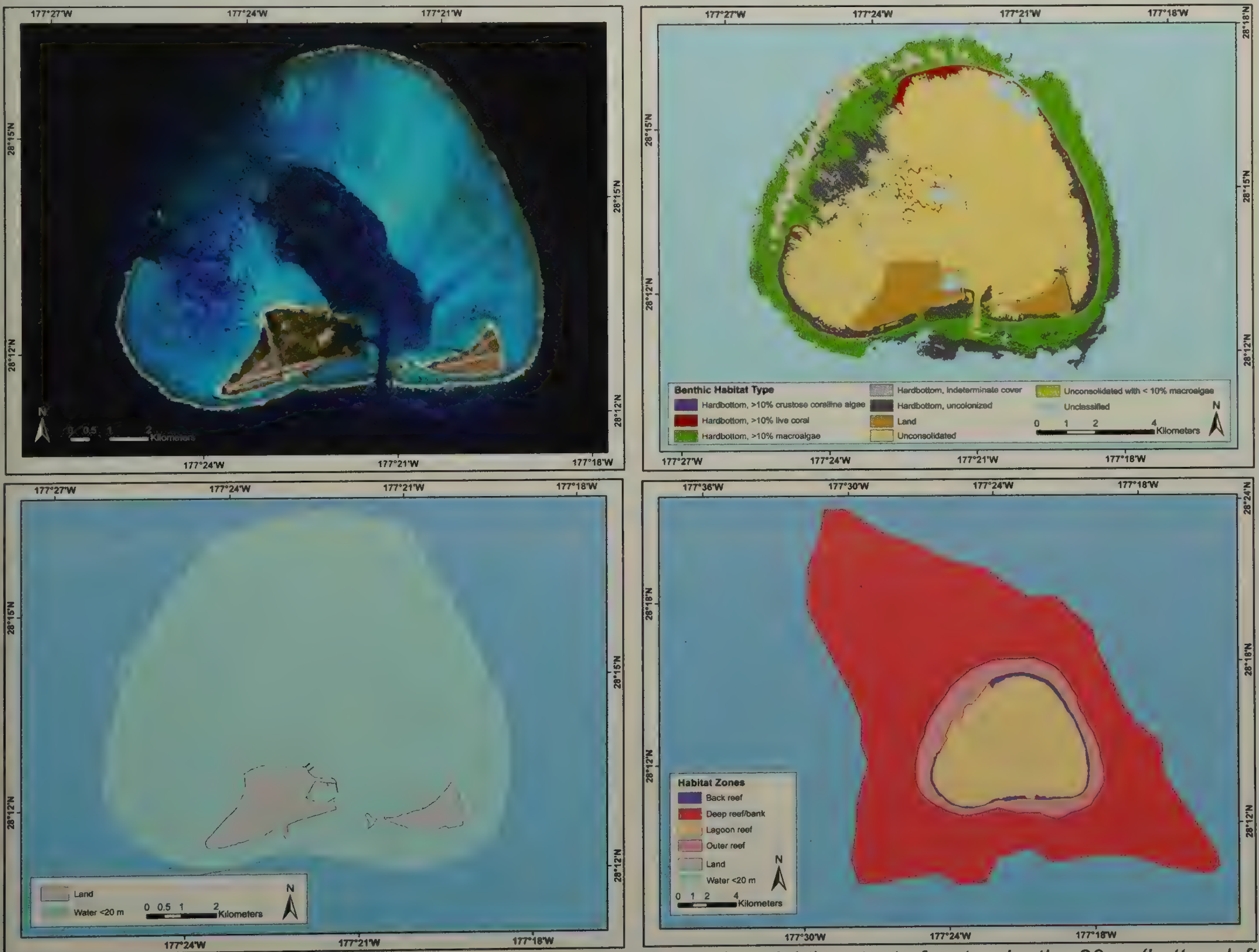


Figure 3.42. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth <20 m (bottom left) and habitat zones (bottom right) for Midway Atoll. Maps: L. Wedding.

mapping (Figure 3.43). Slope increased by 10 fold between the shallowest and intermediate depth with a modest decline in the deepest depth bin. Aspect ratio increased moderately between shallow and intermediate depth but declined sharply in the 588-1,045 m depth range. Rugosity increased from shallow to intermediate before declining slightly in the deepest depth range (Table 3.12).

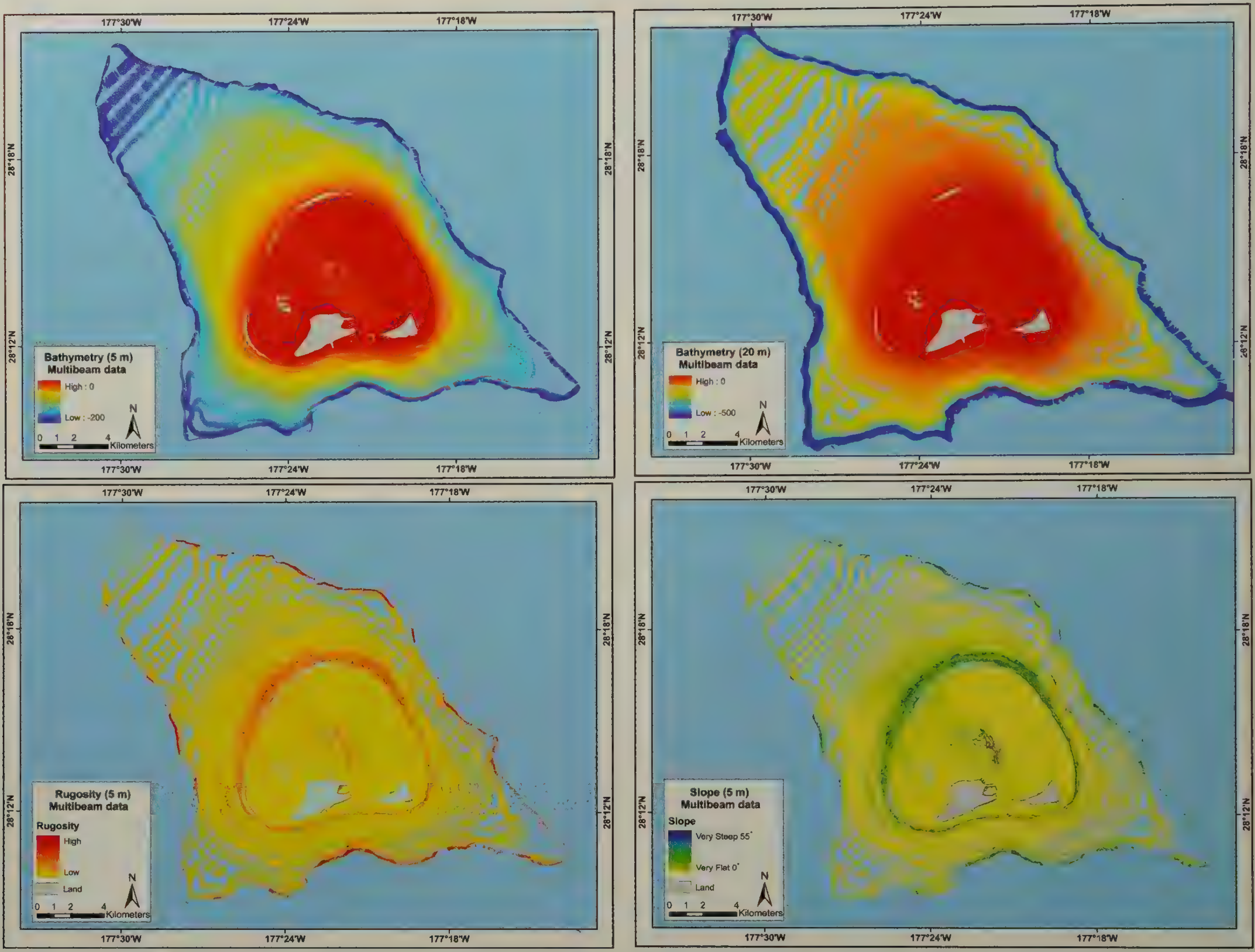


Figure 3.43. 5 m and 20 m bathymetry, rugosity (5 m), and slope (5 m) for Midway Atoll with derived depths from IKONOS imagery near island center. Maps: L. Wedding.

Table 3.12. Summary statistics for multibeam surveys conducted around Midway Atoll (2003-2006).

MIDWAY	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	306.19	-250.60	3.00	253.60	-60.98	51.15
	266 to 588	37.32	-500.00	2.00	502.00	-349.27	77.63
	588 to 1,046	0.00	-2.00	-2.00	0.00	-2.00	0.00
Slope	9 to 226	-	0.00	56.57	56.57	2.85	5.16
	266 to 588	-	0.00	79.34	79.34	28.83	9.04
	588 to 1,046	-	19.97	19.97	0.00	19.97	0.00
Aspect	9 to 226	-	-1.00	360.00	361.00	137.68	114.67
	266 to 588	-	-1.00	360.00	361.00	170.08	95.52
	588 to 1,046	-	40.82	40.82	0.00	40.82	0.00
Rugosity	9 to 226	-	1.00	2.29	1.29	1.01	0.04
	266 to 588	-	1.00	4.87	3.87	1.19	0.16
	588 to 1,046	-	1.11	1.11	0.00	1.11	0.00

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

Kure Atoll

Kure Atoll is the most northwestern island in the Hawaiian chain and occupies a singular position at the "Darwin Point": the northern extent of coral reef development, beyond which coral growth cannot keep pace with the rate of geological subsidence. Kure's coral is still growing slightly faster than the island is subsiding. North of Kure, where growth rates are even slower, the drowned Emperor Seamounts foretell the future of Kure and all of the Hawaiian Archipelago. As Kure Atoll continues its slow migration atop the Pacific Plate, it too will eventually slip below the surface (Grigg, 1982).

This 29.8 million year old atoll (Clague, 1996) is nearly circular, with a reef 9.6 km in diameter enclosing a lagoon with two islets that include over 0.81 km^2 of emergent land, flanked by almost 324 km^2 of coral reef habitat (Figures 3.44, 3.45). The outer reef forms a nearly complete circular barrier around the lagoon, with the exception of passages to the southwest. Of the two enclosed islets, the only permanent land is found on crescent-shaped Green Island, which rises to 6.1 m above sea level and is located near the fringing reef in the southeastern quadrant of the lagoon. The USCG established a LORAN station at Kure in 1960 (Woodward, 1972) and occupied it until 1993. This land use had far-reaching effects on all the plants and animals at Kure Atoll, resulting in elevated invasive species problems and contaminants left behind when the base closed.

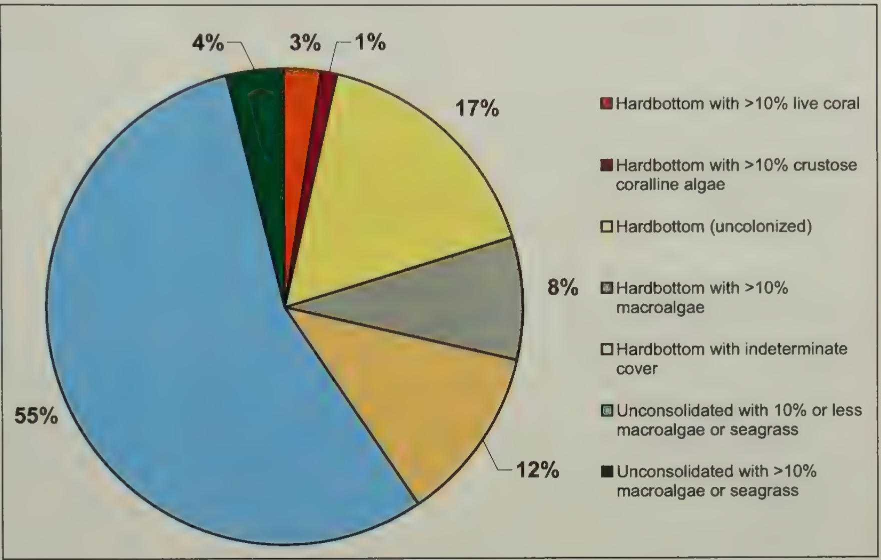


Figure 3.44. Percent composition of mapped benthic habitats at Kure Atoll based on NOAA benthic habitat maps. Source: NOAA, 2003.

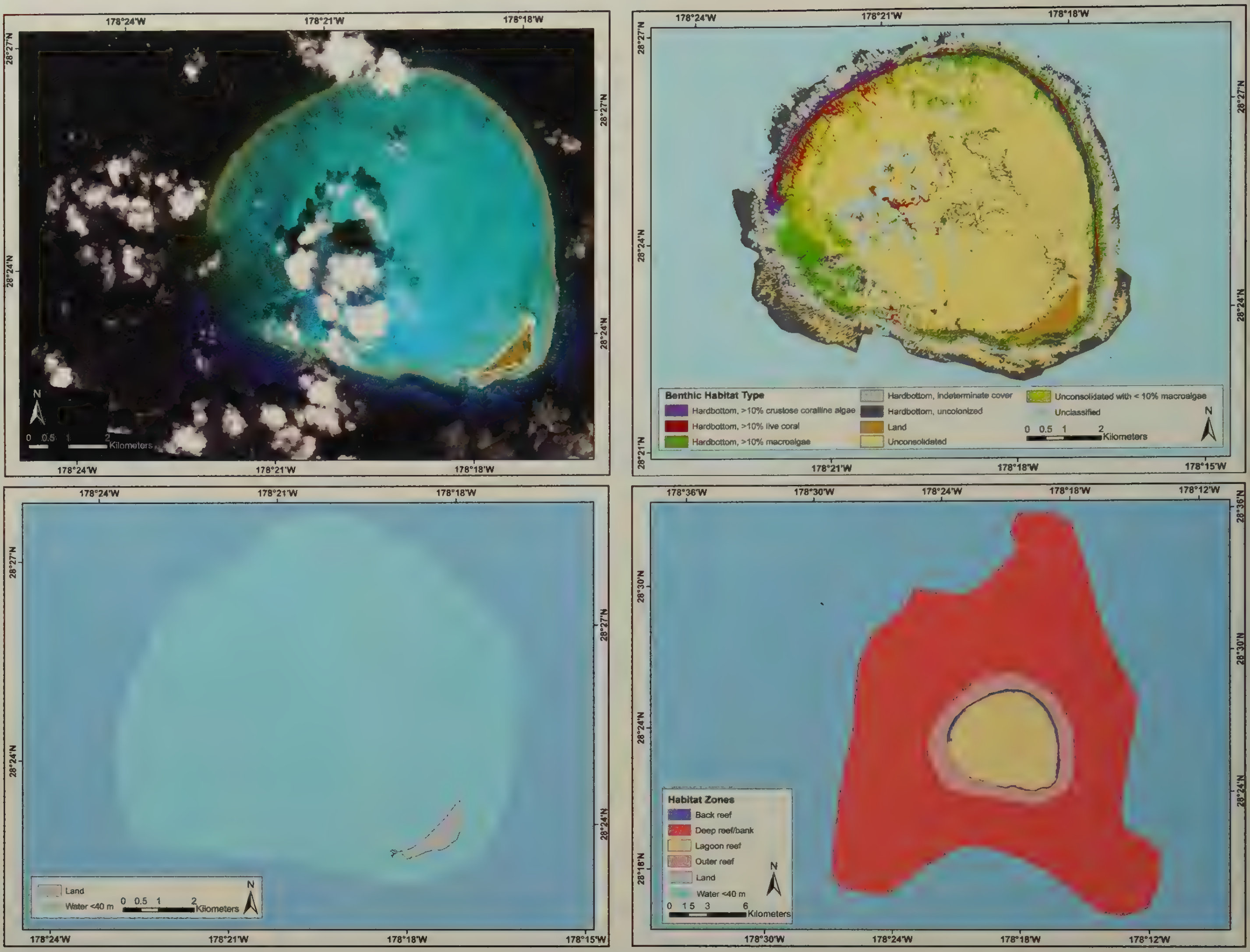


Figure 3.45. IKONOS satellite image (top left), benthic habitat map (top right), extent of water depth < 20 m (bottom left), and habitat zones (bottom right) for Kure Atoll. Maps: L. Wedding.

Multibeam data were collected around Kure Atoll in 2005 (HI0509) to delineate the 25, 50 and 100-fm boundaries and in 2006 (HI0609) to complete mapping of the atoll (Figure 3.46). Slope increased by 9 fold between the shallow and intermediate depth ranges (Table 3.13). Aspect ratio and rugosity also showed the same trend although the magnitude was not as great (Figure 3.47). Multibeam bathymetry at Kure and Midway show extensive spur and groove formations in the high resolution data.

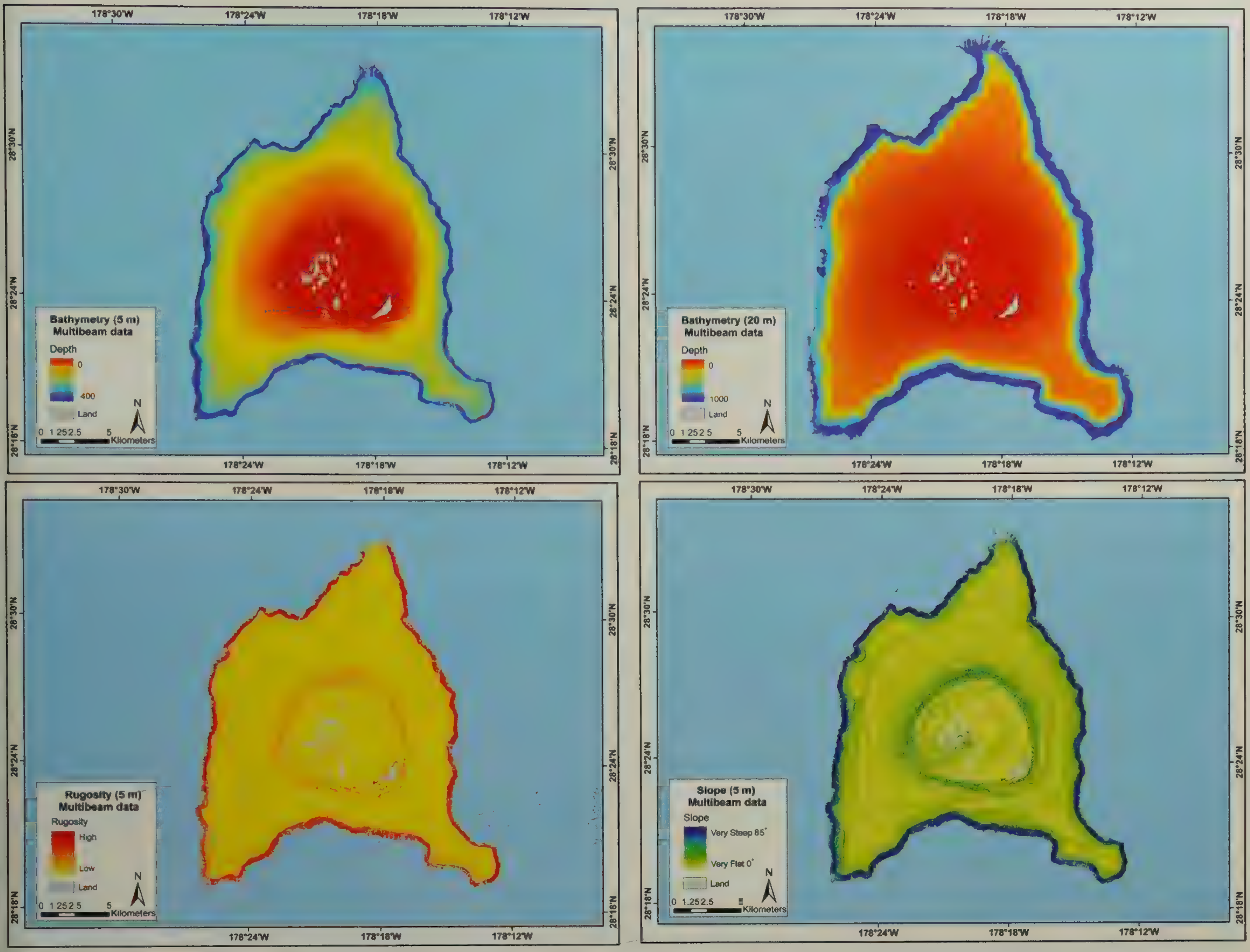


Figure 3.46. 5 m and 20 m bathymetry, rugosity (5 m), and slope (5 m) for Kure Atoll. Maps: L. Wedding.

Table 3.13. Summary statistics for multibeam surveys conducted around Kure Atoll (2005-2006).

KURE	DEPTH CLASS	AREA	MINIMUM*	MAXIMUM*	RANGE	MEAN	STANDARD DEVIATION
Bathymetry	9 to 226	323.34	-225.00	1.00	226.00	-73.27	52.46
	266 to 588	30.76	-402.00	-226.00	176.00	-314.77	50.63
Slope	9 to 226	-	0.00	77.44	77.44	2.86	4.68
	266 to 588	-	0.00	77.82	77.82	26.69	8.43
Aspect	9 to 226	-	-1.00	359.43	360.43	153.84	117.63
	266 to 588	-	-1.00	359.79	360.79	183.77	97.63
Rugosity	9 to 226	-	1.00	7.63	6.63	1.01	0.03
	266 to 588	-	1.00	8.12	7.12	1.15	0.12

***NOTE:** the minimum represents the minimum value of a given metric within a universal depth class; maximum represents the maximum value of a given metric within a universal depth class.

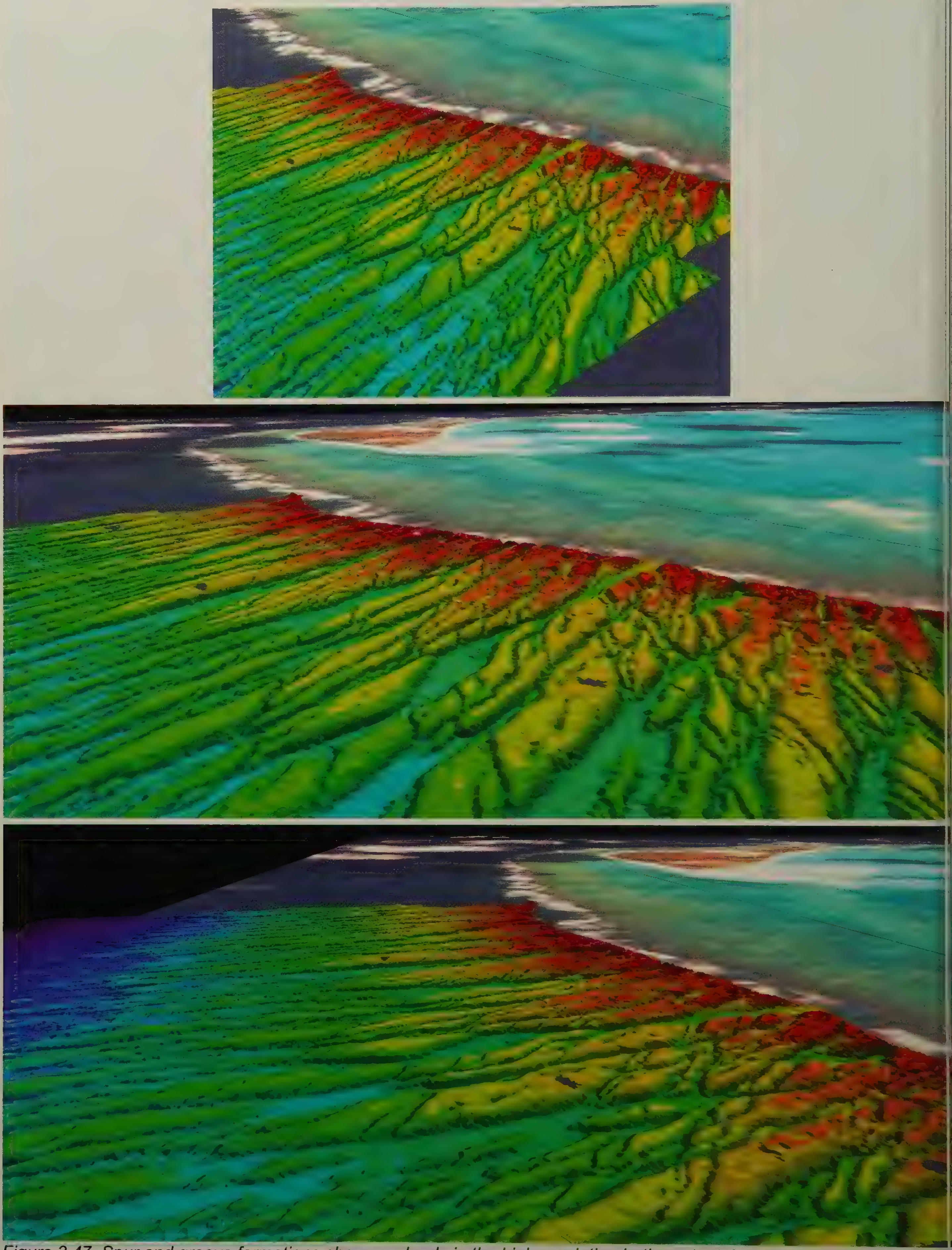


Figure 3.47. Spur and groove formations show up clearly in the high resolution bathymetry taken around Kure Atoll.

EXISTING DATA GAPS

- A comprehensive shallow-water benthic habitat map is required to support multiple research and monitoring activities. Currently only about 50% of the shallow-water area from 0-30 m has sufficient coverage and quality of imagery to produce maps.
- A complete and seamless digital terrain and bathymetric models for the Papahanaumokuakea Marine National Monument (PMNM) to at least 500 m is currently lacking and is necessary to better understand the connection of shallow and deep-water habitats. It will also help guide assessment and monitoring activities.
  - Need to complete high-resolution multibeam bathymetry for shallow to moderate (20 to 500 m) depths.
  - Need to collect shallow (<20 m) bathymetric data using Light Detection and Ranging (LIDAR) or other appropriate technologies.
- Sea level curves developed from the MHI and elsewhere around the Pacific might not be appropriate for the NWHI. Fossil coring and other methods should be employed to better understand past sea level changes in the NWHI.
- Need to determine whole reef accretion rates in different geomorphological zones.
- Need to examine rates of terrestrial habitat loss and the factors that cause it.

REFERENCES

Clague, D.A. 1996. The growth and subsidence of the Hawaiian-Emperor volcanic chain. Pp: 35-50. In: Keast A., S.D. Miller (eds.). The origin and evolution of the Pacific Island biota, New Guinea to Eastern Polynesia: patterns and processes. SPB Academic Publishing, Amsterdam, The Neatherlands.

Clague, D.A. and G.B. Dalrymple. 1987. The Hawaiian-Emperor volcanic chain: Part I. Geologic evolution. US Geological Survey Professional Paper 1350, pp. 5-54.

Clapp, R.B. 1972. The natural history of Gardner Pinnacles, northwestern Hawaiian Islands: botany. Atoll Res. Bull., no.163.

Davies, T.A., P. Wilde, and D.A. Clague. 1972. Koko seamount: a major guyot at the southern end of the Emperor seamounts. Mar. Geol. 13: 311-321.

Garcia, M., D. Grooms, and J. Naughton. 1987. Petrology and geochronology of volcanic rocks from seamounts along and near the Hawaiian Ridge. Lithos 20: 323-336.

Grigg, R. W. 1981. Coral reef development at high latitudes in Hawaii, Proceedings of the Fourth International Coral Reef Symposium, Manila, 1, 687-693.

Grigg, R.W. 1982. Darwin Point: a threshold for atoll formation. Coral Reefs 1: 29-34.

Grigg, R.W. 1983. Community structure, succession and development of coral reefs in Hawaii. Mar Ecol Prog Ser 11:1-14.

Grigg, R.W. 1997. Paleoceanography of coral reefs in the Hawaiian-Emperor Chain – Revisited. Coral Reefs 16, Suppl:S33-S38.

Grigg, R.W., J. Polovina, A. Friedlander, and S. Rohmann. 2008. Pp: 573-594 in: Biology and paleoceanography of the coral reefs in the northwestern Hawaiian Islands. In: Coral reefs of the United States (B. Riegl and R. Dodge, eds.). Springer-Vergal Publishing.

Gross M.G., J.D. Milliman, J.I. Tracey, and H.S. Ladd. 1969. Marine geology of Kure and Midway Atolls, Hawaii: a preliminary report. Pac. Sci. 23:17-25.

Hoeke, R., R. Brainard, R. Moffitt, and M. Merrifield. 2006. The role of oceanographic conditions and reef morphology in the 2002 coral bleaching event in the northwestern Hawaiian Islands. Atoll Res. Bull. 543:489-503.

Jackson, E. D.; Shaw, H. R.; Bargar, K. E. Calculated geochronology and stress field orientations along the Hawaiian chain.Earth and Planetary Science Letters, Vol. 26, p.145

Jenness, J. 2003. Grid surface areas: surface area and ratios from elevation grids [electronic manual]. URL http://www.jennessent.com/arcview/arcview_extensions.htm

Juvik, S.P. and J.O. Juvik. 1998. Atlas of Hawaii, 3rd edition. University of Hawaii Press. Honolulu.

Lundblad, E., D.J. Wright, J. Miller, E.M. Larkin, R.B. Rinehart, S.M. Anderson, D.F. Naar, and B.T. Donahue. 2006. A benthic terrain classification scheme for American Samoa. Marine Geodesy 29: 89-111.

Maragos, J.E., D.C. Potts, F. Aeby, D. Gulko, J. Kenyon, D. Siciliano, and D. VanRavenswaay. 2004. 2000-2002 Rapid Ecological Assessment of Corals (Anthozoa) on Shallow Reefs of the Northwestern Hawaiian Islands. Part 1. Species and Distribution. Pacific Science 58(2): 211-230.

Miller, J.E., R.K. Hoeke, T.B. Appelgate, P.J. Johnson, J.R. Smith, and S. Bevacqua. 2003. Atlas of the Northwestern Hawaiian Islands, Draft – February 2004, National Oceanic and Atmospheric Administration, 65 pp.

Neall, V.E. and S.A. Trewick. 2008. The age and origin of the Pacific islands: a geological overview. Phil. Trans. R. Soc. B 363:3293-3308.

NOAA (National Oceanic and Atmospheric Administration). 2003. Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands (Draft). 160 pp.

Parrish, F.A. and J.J. Polovina. 1994. Habitat thresholds and bottlenecks in production of the spiny lobster (*Panulirus marginatus*) in the northwestern Hawaiian Islands. Bulletin of marine science 54: 151-163.

Rohmann, S.O., J.J. Hayes, R.C. Newhall, M.E. Monaco, and R.W. Grigg. 2005. The area of potential shallow-water tropical and subtropical coral ecosystems in the United States. Coral Reefs 24:370-383.

Rooney, J.J., P. Wessel, R. Hoeke, J. Weiss, J. Baker, F. Parrish, C.H. Fletcher, J. Chojnacki, M. Garcia, R. Brainard, and P. Vroom. 2008. Geology and Geomorphology of Coral Reefs in the Northwestern Hawaiian Islands. In: Coral reefs of the United States (B. Riegl and R. Dodge, eds.). Springer-Vergal Publishing.

Stumpf, R.P. and K. Holderied. 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types. Limnol. Oceanogr. 48: 547-556.

Stumpf, R.P., K. Holderied, and M. Sinclair. 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types. Limnology and Oceanography 48: 1.

Woodward, P.W. 1972. The natural history of Kure Atoll, Northwestern Hawaiian Islands. Atoll Res. Bull. 164:1-317.

WEBSITES

NOAA. 2008. http://ccma.nos.noaa.gov/ecosystems/coralreef/nwhi/welcome.html

NOAA. 2008. http://biogeo.nos.noaa.gov

UH SOEST. 2008. http://www.soest.hawaii.edu/pibhmc/pibhmc_nwhi.htm

NOAA. 2008. http://biogeo.nos.noaa.gov

Benthic Communities

James Maragos[1], Jean Kenyon[2,3], Greta Aeby[4], Peter Vroom[2,3], Bernardo Vargas-Angel[2,3], Russell Brainard[2], Lisa Wedding[4,5], Alan Friedlander[5,6], Jacob Asher[2,3], Brian Zgliczynski[2] and Daria Siciliano[7]

INTRODUCTION

This chapter focuses on the shallow water benthos surrounding the 10 emergent islands, reefs and atolls comprising the Northwestern Hawaiian Islands (NWHI). The composition and distribution of benthic communities in the subtropical NWHI reflect the interaction of numerous influences, including geographic isolation, latitude, exposure and the successional age of the islands they inhabit. This mosaic of habitats extend 1,200 nm northwest of the main Hawaiian Islands (MHI) and consist mostly of coral-dominated areas, stretches of hard-bottom algal-dominated meadows, and vast expanses of unconsolidated sediments such as sand and mud inhabited by few benthic infauna at shallower depths (<20 m). The benthic habitats at greater depths are relatively unknown, unexplored and are not covered here.

CORALS

Species Richness

The most recent published surveys of the NWHI revealed a total of 57 species of zooxanthellate stony corals (Maragos et al., 2004). However 2006 surveys at greater depths and in a wider variety of habitats have yielded a number of new morpho-species, most of which have yet to be collected and described. Appendix I lists of all coral and anemone species reported at 11 islands, banks, atolls and reefs in the NWHI as of October 2006. As was the case during earlier compilations, the larger atolls with diverse habitats and shelter from large northwest swell support the greatest number of species. Although these numbers are similar to the MHI, the Hawaiian coral fauna, as a whole, is depauperate relative to the Indo-West-Pacific, where up to 700 species have been reported (Veron, 1995). The most plausible cause is geographic isolation (Grigg, 1983) associated with the NWHI being located at the northeastern periphery of the Indo-Pacific biogeographic province.

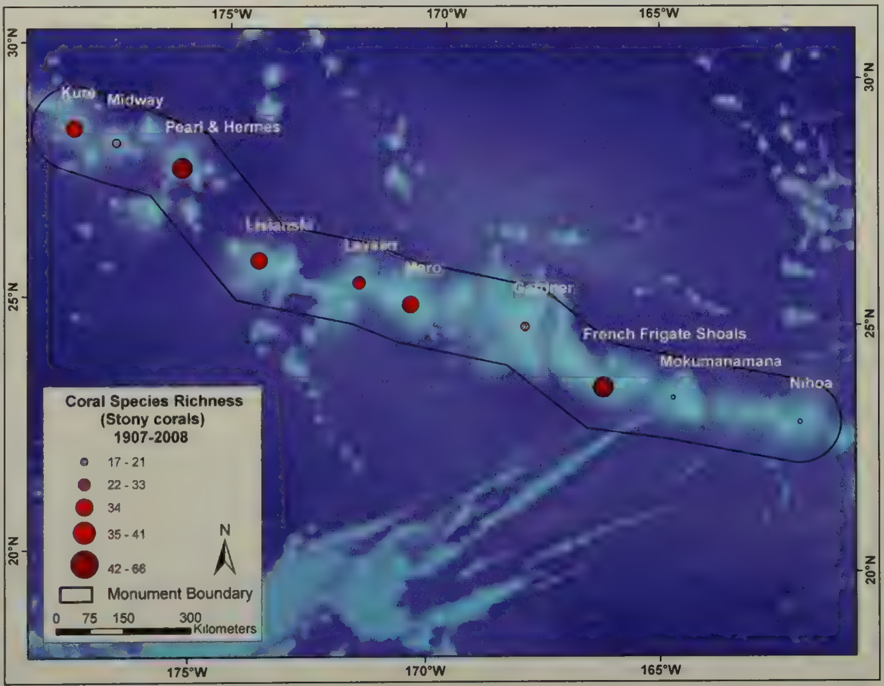


Figure 4.1. Total number of coral species reported in the NWHI between 1907 and 2006 compiled by Maragos from Dana (1846), Vaughan (1907), Dana (1971), Maragos et al. (2004) and unpublished records. Map: L. Wedding.

The distribution of coral species is related to geomorphology, size and age of the NWHI reefs (Grigg, 1997; Figure 4.1). There is a highly significant ($p< 0.001$) correlation between the number of coral taxa and the amount of reef area within 10 fathoms with French Frigate Shoals, Pearl and Hermes and Maro

---

1. U.S. Fish and Wildlife Service
2. NOAA/NMFS/Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division
3. Joint Institute for Marine and Atmospheric Research
4. University of Hawaii at Manoa
5. NOAA/NOS/NCCOS/CCMA Biogeography Branch
6. The Oceanic Institute
7. University of California Santa Cruz, Institute of Marine Sciences

Reef having the highest richness of coral taxa (Table 4.1, Figure 4.2). Low coral species richness is found at the southern end among the small basalt islands of Nihoa, Mokumanamana and Gardner Pinnacles, which are openly exposed to severe wave events particularly during winter months (Maragos et al., 2004 ; Grigg et al., 2008). This area is dominated by robust species that are more tolerant of high wave action and soft corals such as *Sinularia* spp. and *Palythoa* spp. The large middle atolls (French Frigate Shoals and Maro) have some of the highest coral species richness reflecting optimal conditions in terms of both habitat (a large open atoll) and environmental conditions (wave shelter, temperature and low disturbance, as well as the high number of Acroporidae and Fungiidae species). Seven species of the genus *Acropora* are now known from the NWHI despite their almost complete absence in the MHI (Maragos et al., 2004), and several additional undescribed *Acropora* were photographed at French Frigate Shoals, Neva Shoal and Pearl and Hermes in 2006. Compared to French Frigate Shoals, Pearl and Hermes Atoll and Maro Reef, one-third fewer coral species are found at Mokumanamana and Nihoa islands. At the northern end of the chain, stony coral species decline is linked to lower winter water temperatures and lower average annual solar radiation (Grigg, 1982), and coral development is limited by extensive sand shallows towards the eastern sides of the lagoons (Maragos et al., 2004). Moreover WWII era construction may have extirpated some corals from Midway's lagoon. Kure is the world's most northern atoll and is referred to as the Darwin Point, where coral growth and subsidence/erosion balance one another (Grigg, 1982). However, there are at least 30 submerged and presumably drowning seamounts to the southeast of Kure and within the PMNM, and the "Darwin point" may be better characterized as a Darwin zone stretching from Nihoa to Kure.

Table 4.1. Least squares linear regression model for reef area less than 10 fathoms versus coral taxa richness. Source: Maragos, unpub. data.

SUMMARY OF FIT				
R^2	0.79859			
R^2 Adjusted	0.773414			
Root Mean Square Error	6.390495			
Mean of Response	35.7			
Observations (or Sum Wgts)	10			
ANALYSIS OF VARIANCE				
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	1	1295.393	1295.39	31.7199
Error	8	326.7074	40.84	**Prob > F**
C. Total	9	1622.1		0.0005
PARAMETER ESTIMATES				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	24.88415	2.7878	8.93	<.0001
Reef area < 10 fathoms	0.072376	0.012851	5.63	0.0005

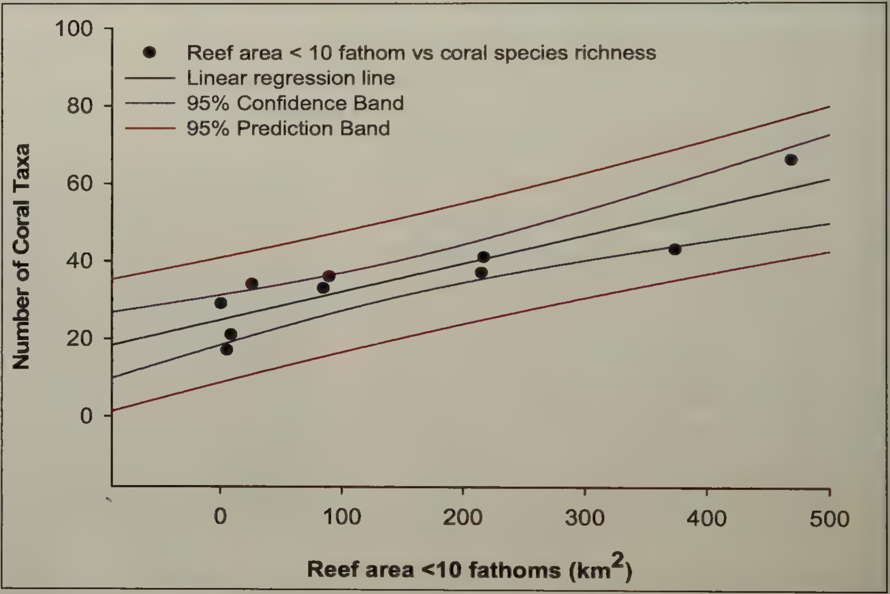


*Figure 4.2. Relationship between number of coral taxa and reef area within 10 fathoms (based on Rohman et al., 2005). Coral species richness = 24.88 + 0.072*Reef area <10 fathoms. Source: Maragos, unpub. data.*

Examination of reefs in ordination space based on presence-absence of coral taxa reveal two major clusters (Figure 4.3). High concordance exists among the basalt islands of Nihoa (NIH), Mokumanamana (MMM) and Gardner Pinnacles (GAR). These small islands are exposed to high wave energy from all directions and have low coral richness and cover. The reefs from Maro (MAR) north to Kure (KUR) cluster together in ordination space but the three most northern atolls (Midway [MID], Pearl and Hermes [PHR], and Kure [KUR]) show the highest concordance. The coral assemblage at French Frigate Shoals appears unique compared with all other locations likely due to the high proportion of acroporid species and possible connectivity with Johnston Atoll 830 km to the south (Grigg et al., 1981; Maragos and Jokiel, 1986).

Range Extensions and Possible New Coral Species

Recent scientific expeditions in the NWHI have yielded many new records and possibly many undescribed species of stony corals since the last compilation by Maragos et al. (2004; Table 4.2). One of the most exciting discoveries in 2006 was of the table coral *Acropora* off the southwest spur-and-groove habitat at Pearl and Hermes Atoll and off the shallow southeast fore reef at Neva Shoal. Additional dives confirmed the presence of *Acropora cytherea* and *A. cerealis-valida* at Pearl and Hermes, and *A. valida* at Neva Shoal, which led to other discoveries at Neva, a second *Acropora* sp.1 and three *Montipora* species that are all likely new to science.

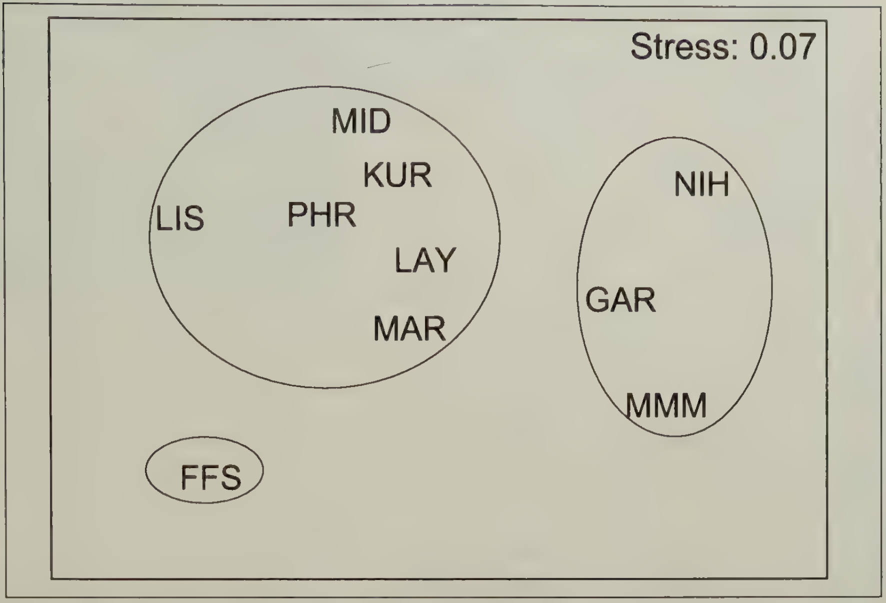


Figure 4.3. Spatial distribution of reefs in the PMNM based on presence-absence of coral species. Results of non-metric multidimensional scaling plot. Source: Maragos, unpub. data.

The Census of Marine Life (CoML) cruise to French Frigate Shoals in October 2006, led to additional sightings of rare species including *Diaseris distorta, Cycloseris tenuis, Leptoseris scabra* and *Acropora* sp.1. Another rare species, resembling *Leptoseris papyracea* was previously known only from dredge hauls by Vaughan (1907) in the MHI, and was reported for the first time in the NWHI off the southeast fore reef of French Frigate Shoals during CoML. An unidentified species, *Porites* sp. 15, was reported off a southwest pinnacle of French Frigate Shoals, and the first record of *Porites lutea* in the NWHI was reported off the northern reef crest. Many new records including several unidentified species of coral were reported during the CoML cruise. The 2006 investigations together have yielded possibly 11 new records for the NWHI most of which are likely to reveal new species. Towed-diver surveys contributed directly or indirectly to several of the new records and species, and exploratory dives in new habitats and sites contributed the rest. The Appendix at the end of the chapter lists all coral and anemone species reported at 11 islands, banks, atolls and reefs in NWHI as of October 2006. As was the case during earlier compilations, the larger atolls with diverse habitat and shelter from large northwest swell support the greatest number of species.

Table 4.2. A partial list of new records and possible new coral species from the NWHI. Source: Maragos, unpub. data.

SPECIES		LOCATION	YEAR	OBSERVERS
Leptoseris incrustans	New record	Pearl and Hermes	2006	Kenyon, PIFSC-CRED
Montipora	New species?	Pearl and Hermes	2006	Vargas, PIFSC-CRED
Acropora valida	New record	Laysan	2006	Kenyon, PIFSC-CRED
Pavona maldivensis	New record	Maro	2006	Kenyon, PIFSC-CRED
Diaseris distorta, Cycloseris vaughani, and *Cycloseris tenuis* and soft coral *Sinularia* sp	New record	Lisianski (30m)	2006	Maragos, Meyer, and Papastamatiou
Acropora cytherea and *A. cerealis-valida*	New record	Pearl and Hermes	2006	Asher and Zgliczynski
Acropora valida	New record	Neva Shoal	2006	Asher and Zgliczynski
Diaseris distorta, Cycloseris tenuis, Leptastrea scabra	New record	French Frigate Shoals	2006	CoML
Leptoseris papyracea??	New record	French Frigate Shoals	2006	CoML
Acropora sp.1	New species?	French Frigate Shoals	2006	CoML
Porites sp. 15	New species?	French Frigate Shoals	2006	CoML
Porites lutea	New record	French Frigate Shoals	2006	CoML
Unkown species	New species?	French Frigate Shoals	2006	CoML

Abbreviations: PIFSC-CRED: The Pacific Islands Fisheries Science Center Coral Reef Ecosystem Division; CoML=Census of Marine Life.

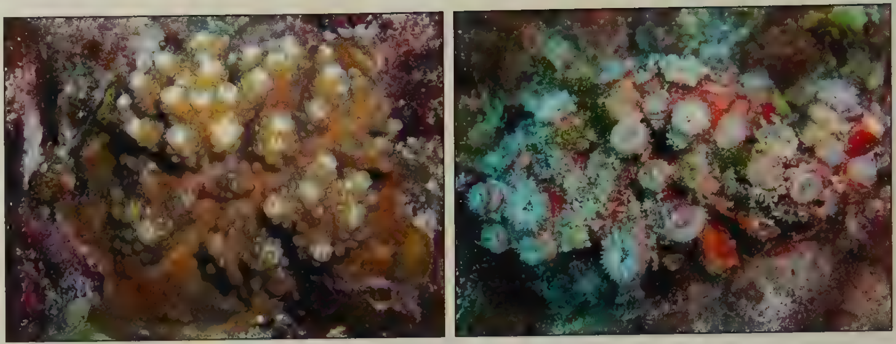


Figure 4.4. Potential new species of Acropora sp.1 from Lisianski-Neva Shoals and French Frigate Shoals (left). New, potential relict species yet undescribed from French Frigate Shoals. The genus and family are unknown (right). Both were discovered in 2006. Photo: J. Maragos.

The most exciting coral discovery was of an unknown species that has not yet be identified to the genus and family (Figure 4.4). This coral may be a relict that was once common in the past and subsequently died out elsewhere but survived in Hawaii. The other possibility is that the coral may be a type previously restricted to deep water that evolved and subsequently adapted itself to shallow water habitats. Randall (2007) makes note of two fish that were previously characterized as relicts. Likewise it is possible for relict corals to have survived in Hawaii to this day. In order to confirm this, it will be necessary to collect this and other corals to determine their phylogenetic origin. So far coral experts have not been able to conclusively determine the family to which this coral belongs based on photographs alone. Marine life in the NWHI evolved for many millions of years in isolation from neighboring archipelagos and islands and it plausible that this, and perhaps other species, were able to survive and thrive without the threat of newer species displacing them as likely occurred in other archipelagos.

French Frigate Shoals was chosen as the target for the first CoML cruise because of the potential of yielding new species of corals, other invertebrates and benthic algae and possibly extending the range of many other species. Eight more species of cnidarians have already been reported from the atoll, further cementing the atoll's status as the most diverse island or atoll for corals in Hawaii. The atoll is the closest of the Hawaiian chain to Johnston Atoll, some 450 nm to the southwest, and Johnston may be serving as a "stepping stone" for the dispersal of species to Hawaii from the Line Islands and other neighboring archipelagos south of Hawaii (Grigg, 1981; Maragos and Jokiel, 1986; Maragos et al,. 2004). This connection would explain why French Frigate Shoals has so many *Acropora* species which flourish at Johnston and why French Frigate Shoals has higher numbers of coral species compared to any of the other Hawaiian Islands.

Coral Endemism

The resumption of coral surveys to the NWHI in 2000-2006 were not focused on looking for new coral species because they were not expected to be there based on the Grigg and Dollar (1980) estimate of only 29 total species at 80 NWHI sites. Although endemic species and range extensions were encountered during the 2000-2006 surveys, most belonged to described species, although the totals nearly doubled the number of coral species (57) reported in the NWHI (Maragos et al., 2004). The exploratory and CoML expeditions of 2006 were both focused on looking for new species. However, scientists could only photograph and examine corals *in situ* because permission was not granted to collect corals.

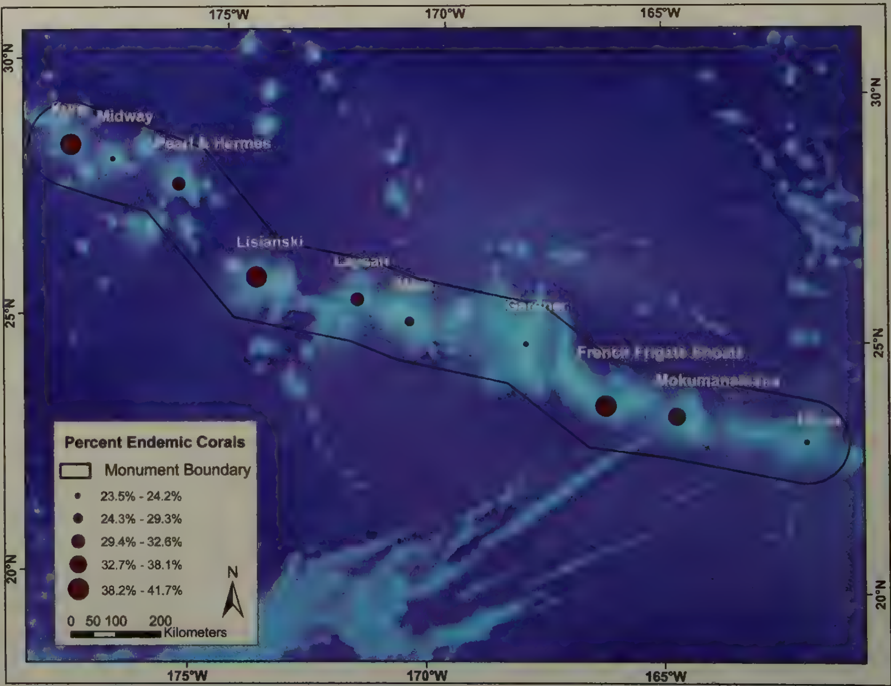


Figure 4.5. Percent endemic stony coral species at each reef in the NWHI during 1907-2006 compiled by Maragos from Dana (1846), Vaughan (1907), Dana (1971), Maragos et al. (2004) and unpublished records. Map: L. Wedding.

Based on all surveys to date (Figure 4.5; Table 4.3) , there are now approximately 80 morphologically distinct coral "species" in the NWHI, and about 35 are likely to be endemic. Perhaps an additional five species are similarly endemic, although other specialists (Veron, 2000) believe they are widespread Pacific species. More than 25 NWHI species are still undescribed or unidentified, and once type specimens are collected and examined morphologically and genetically, then final determinations can be made on which corals are new species and possible endemics. Notwithstanding efforts to date, NWHI explorations are still inadequate, and it is likely that additional undescribed coral species will be encountered in the future.

Coral Cover From Quantitative Surveys

Percent live coral cover was derived from towed-diver data and rapid ecological assessments (REAs; Kenyon et al,. 2006a; Table 4.4; Figures 4.6 and 4.7). Towed-divers observe a much greater expanse of benthic reef habitat (approximately 2 km in length/50 minute tow) than can be observed by free-swimming divers conducting REA surveys in a comparable time period and give a more widespread assessment of the total coral cover for each reef. Coral REA surveys were conducted at 70 sites in 2004, 37 sites in 2005 and 64 sites in 2006 (Table 4.4). As with percent cover data from 2002 surveys (which were calculated from size frequency data of colony counts within transects; Friedlander et al.; 2005), line-intercept data from surveys in all three years indicated coral cover varies greatly across the NWHI.

Based on towed-diver survey data, Lisianski (18.8%) and Maro (14.9%) have the highest coral cover, followed by French Frigate Shoals (Figure 4.6). Percent coral cover from the REAs is higher owing to the fact that they were conducted on hard bottom habitats only. However, the trends are strikingly simi-

Table 4.3. Number of endemic and total stony coral taxa among major reefs in the PMNM. Source: Maragos, unpub. data.

ISLAND	TOTAL STONY CORAL SPECIES	NUMBER OF ENDEMIC	PERCENT ENDEMIC
Nihoa	17	4	23.5
Mokumanamana	21	8	38.1
French Frigate Shoals	66	27	40.9
Gardner	29	7	24.1
Maro	41	12	29.3
Laysan	34	11	32.3
Lisianski	37	15	40.5
Pearl and Hermes	43	14	32.6
Midway	33	8	24.2
Kure	36	15	41.7
Total	**80**	**35**	**44**

Table 4.4. Number of Rapid Ecological Assessments (REA) and Towed-diver Surveys (TDS) conducted by NWHI RAMP (2004 and 2006) and NWHI Ecosystem Reserve (2005). PHR = Pearl and Hermes. Source: NWHI RAMP, unpubl. data.

	2004		2005		2006	
	REA	TDS	REA	TDS	REA	TDS
Mokumanamana	3	0	3	0	2	4
French Frigate Shoals	11	17	6	0	10	19
Gardner	3	2	0	0	0	0
Maro	9	12	7	0	9	13
Laysan	3	5	0	0	3	6
Lisianski	9	12	0	0	9	12
PHR	14	21	9	0	13	26
Midway	9	15	6	0	9	15
Kure	9	13	6	0	9	13
Total	70	97	37	0	64	108

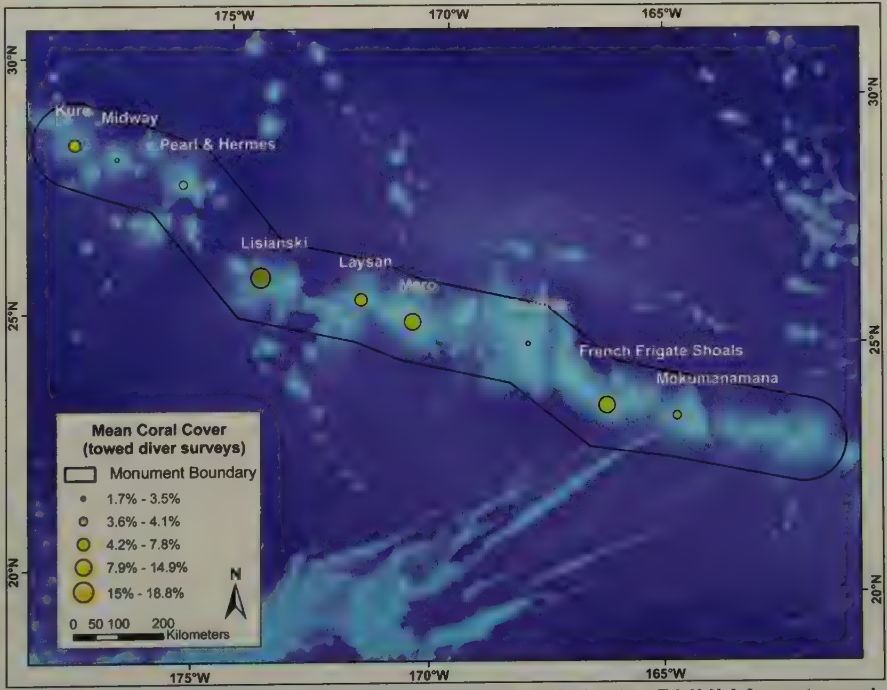


Figure 4.6. Percent live coral cover among reefs in the PMNM from towed-diver survey data, 2000-2002. Source: NWHI RAMP; map: L. Wedding

lar based on average estimates from 2004 to 2006, with the highest coral cover at Maro (39.0%), followed by Lisianski (37.5%) and French Frigate Shoals (26.0%; Figure 4.7). The lowest percent coral cover was recorded at Midway (1.7%), Gardner Pinnacles (3.5%), and Mokumanamana (4.1%). The lowest cover from the REA surveys was observed at Midway (10.1%), with Pearl and Hermes (12.1%) and Gardner Pinnacles (12.4%) also having low coral cover. Benthic REAs were not conducted at Mokumanamana from 2004 to 2006. Coral cover values determined from 2002 surveys also showed the highest coral cover values at Maro and Lisianski (Friedlander et al., 2005), though their magnitude (>60%) was greater than the values derived from the line-intercept method in 2004-2006.

Coral cover estimates for each reef from towed-divers and REAs compared with the mean coral cover for each method showed higher relative towed-diver survey values at Lisianski and French Frigate Shoals (Figure 4.8). This is likely due to the extensive deeper reefs that were not surveyed on the REAs, which are restricted to 15 m depth while towed-diver surveys operate down to 27 m. Higher relative coral cover estimates from REA were found at Nihoa, Midway, and Pearl and Hermes. The latter two locations have extensive back reef habitats that are not well surveyed by towed-divers due to the shallow depth.

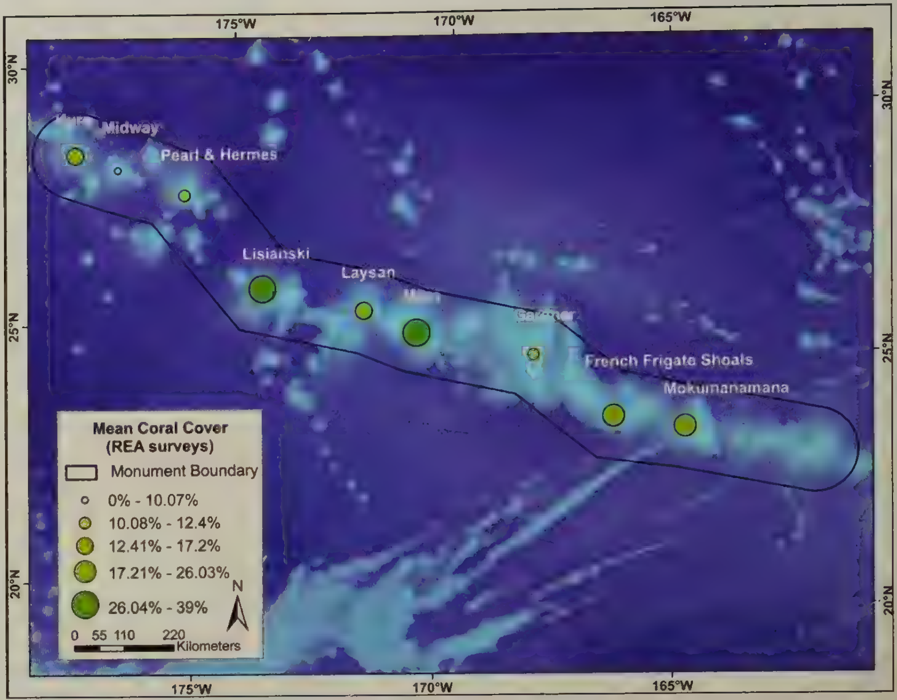


Figure 4.7. Live coral cover among reefs in the PMNM from REA data, 2004-2006. Source: NWHI RAMP; map: L. Wedding

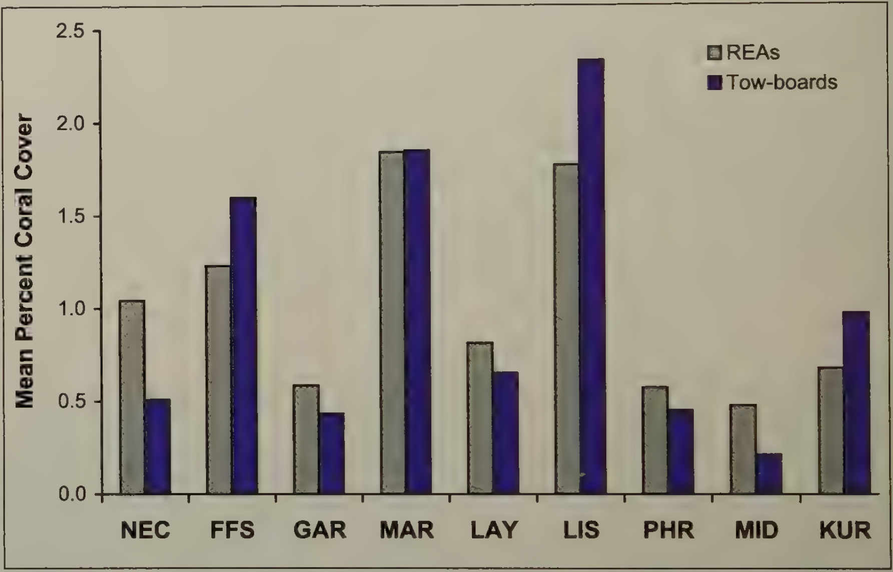


Figure 4.8. Comparisons of coral cover between towed-diver and REA estimates. Values are percent at each reef as a proportion of mean coral cover for that method. Source: NWHI RAMP, unpub. data.

Quantitative Estimates of Coral Genera and Species Abundance Among Reefs of the NWHI

Relative abundance of cnidarians was assessed by computing the proportion of colonies, by taxon, that occurred within belt transects (Table 4.5, Figure 4.9). Taxa comprising more than 10% of colony abundance in each location are highlighted in bold type. These 2006 data surveys exemplify some general patterns seen in all years. The relative abundance of corals varies among regions, though *Porites lobata* composes a majority of the fauna at numerous regions and is an important component of the fauna in all regions. *Acropora*, particularly *A. cytherea,* is an important component of the coral fauna at French Frigate Shoals, but less so in other regions where it occurs (Mokumanamana to Pearl and Hermes, inclusive). *Pocillopora meandrina* and *Montipora capitata* are both abundant in some regions but less common in others. Numerous taxa are represented throughout the NWHI at very low levels of abundance; although 57 species of stony corals have been documented in the NWHI (Maragos et al., 2004), many species occur at such low frequencies that they were not encountered within survey transects. Thus, relatively few coral species numerically dominate throughout the NWHI. When species are pooled by genus, *Porites*, *Pocillopora* and *Montipora* collectively emerge as the numerically dominant genera throughout the NWHI though their relative abundance varies by region (Figure 4.10).

Table 4.5. Relative abundance of cnidarian colonies in the NWHI based on REA surveys at 64 sites conducted by NWHI RAMP in 2006. All cnidarian taxa for which at least one colony was tallied in at least one location are listed. Source: Forsman and Maragos, unpub. data.

SPECIES	**PERCENT OF CNIDARIAN FAUNA**							
	MMM	**FFS**	**MAR**	**LAY**	**LISI**	**PHR**	**MID**	**KUR**
Acropora cytherea	0.0%	**10.7%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Acropora valida	0.0%	5.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Acropora humilis	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Montipora capitata	2.8%	2.6%	**15.1%**	9.4%	**17.7%**	6.3%	1.1%	2.7%
Montipora patula	2.5%	2.5%	5.2%	1.6%	6.8%	1.0%	0.1%	0.0%
Montipora flabellata	0.0%	0.0%	0.7%	0.0%	0.0%	0.5%	**13.6%**	1.9%
Montipora incrassata	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pavona duerdeni	1.9%	2.5%	2.5%	3.8%	2.1%	0.3%	0.0%	0.0%
Pavona varians	0.1%	0.0%	0.0%	2.1%	0.1%	0.3%	0.4%	0.2%
Pavona maldivensis	0.0%	0.0%	0.0%	0.0%	1.1%	0.2%	0.0%	0.0%
Cyphastrea ocellina	0.0%	7.6%	4.8%	4.5%	**18.8%**	1.5%	0.9%	1.5%
Leptastrea purpurea	0.6%	1.0%	0.2%	0.2%	0.3%	7.3%	1.1%	3.6%
Fungia scutaria	0.0%	0.0%	0.5%	0.0%	0.9%	2.4%	0.0%	0.0%
Leptoseris incrustans	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
Pocillopora damicornis	0.0%	6.9%	0.7%	0.0%	6.4%	2.6%	8.5%	**13.4%**
Pocillopora eydouxi	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pocillopora ligulata	0.7%	0.4%	1.2%	0.0%	0.6%	0.1%	0.2%	0.5%
Pocillopora meandrina	**28.9%**	8.1%	6.5%	**17.4%**	1.1%	**26.2%**	**11.3%**	**52.4%**
Porites brighami	0.6%	1.1%	0.3%	3.8%	0.6%	0.0%	0.0%	0.0%
Porites compressa	3.8%	**15.9%**	**39.8%**	1.9%	9.7%	8.5%	6.3%	5.4%
*Porites evermanni**	2.0%	1.5%	1.3%	0.2%	**11.9%**	0.0%	0.1%	0.1%
Porites lobata	**55.3%**	**32.2%**	**20.1%**	**54.9%**	**20.6%**	**37.1%**	**55.9%**	**16.3%**
Psammocora nierstraszi	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Psammocora stellata	0.0%	0.1%	0.0%	0.2%	1.3%	3.3%	0.2%	1.1%
Palythoa sp.	0.6%	1.3%	1.0%	0.0%	0.0%	2.3%	0.1%	0.8%
Total cnidarians counted	689	2,408	2,443	426	1,920	2,319	1,158	1,929
Area surveyed (m²)	100	500	450	100	450	650	425	450

Island/Atoll abbreviations used throughout this chapter: MMM = Mokumanamana; FFS = French Frigate Shoals; and PHR = Pearl and Hermes Atoll; GAR = Gardner Pinnacles; MAR = Maro Reef; LAY = Laysan Island; LIS = Lisianski Island; MID = Midway Atoll; KUR = Kure Atoll; NIH = Nihoa Island.

* *Porites evermanni* is considered to be *Porites lutea* by Fenner 2005, although recent molecular analyses have confirmed that *P. evermanni* is distinct from *P. lutea*.

Coral Density

Density, the number of cnidarian colonies per square meter, is another metric of community structure that reflects the degree of "packing" of individual colonies. Such indices are useful when considering processes that may be density-dependent, for example, the spreading of contagious diseases and fertilization by spawned gametes during sexual reproduction. Colony density should be considered in association with size frequency distributions in visualizing the nature of a population from graphed data, e.g., a high colony density accompanied by a right-skewed size frequency distribution indicates a large number of small colonies, while a low colony density accompanied by a left-skewed distribution indicates a small number of larger colonies. Density varies by taxon and by habitat, as demonstrated for Pearl and Hermes Atoll in Figure 4.11.

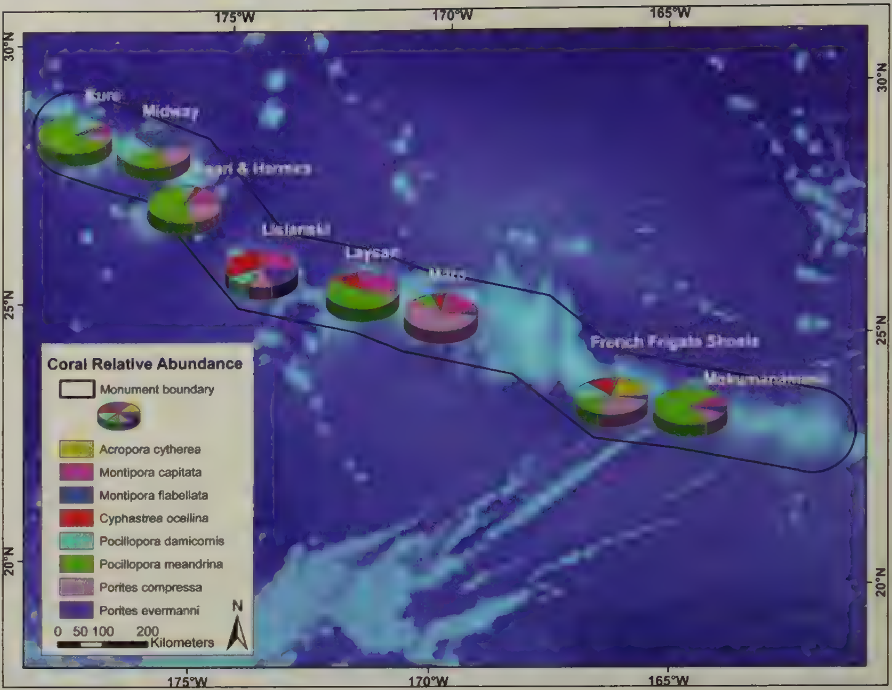


Figure 4.9. Relative abundance of coral species throughout the NWHI. Data are derived from colony counts within belt transects during 2006 surveys. Source: NWHI RAMP unpubl. data; map: L. Wedding.

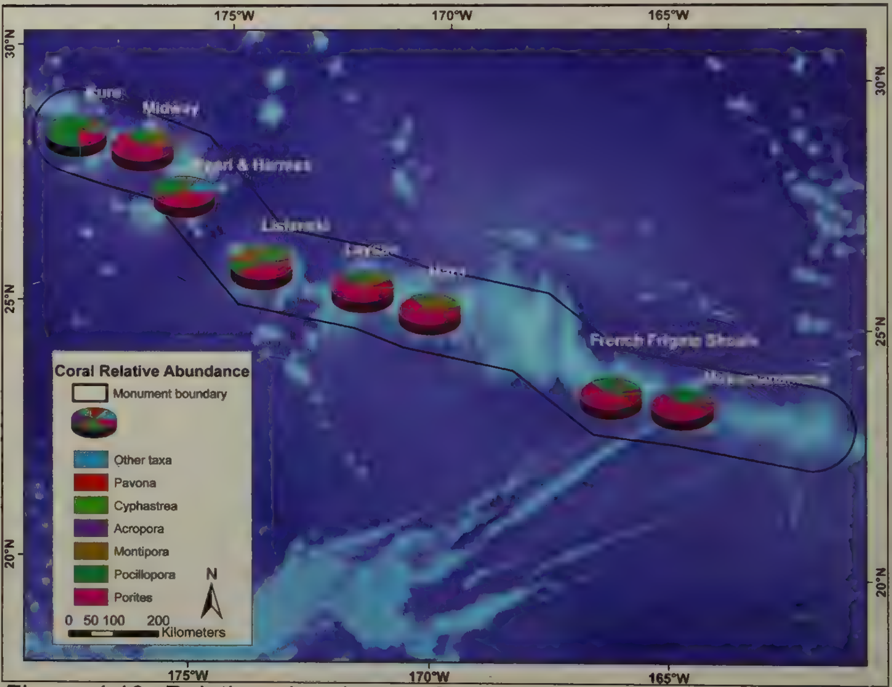


Figure 4.10. Relative abundance of coral genera throughout the NWHI. Data are derived from colony counts within belt transects during 2006 surveys. Source: NWHI RAMP unpubl. data; map: L. Wedding.

Habitat

Coral cover varies among reef geomorphologies and reef zones (Figure 4.12). Maro Reef has been described as a unique open atoll, as it lacks the emergent or very shallow perimeter reef around a deeper lagoon that characterizes a classic atoll. Instead, the innermost area of the reef complex, with characteristics of a protected lagoon, is separated from the open ocean by the surrounding mesh of reticulate, linear, and patch reefs. Average coral cover at Maro, as determined through quantitative analysis of benthic imagery recorded over extensive distances surveyed by towed divers between 2000 and 2002, was 14.0% (Kenyon et al., 2008a). Lisianski/Neva Shoal and French Frigate Shoals are also described as open atolls, the former with limited perimeter reef and the latter lacking perimeter reef to the west. Average coral cover at Lisianski was 19.7%, the highest average reef system value determined from extensive towed-diver surveys throughout the NWHI (Kenyon et al., 2007b). At French Frigate Shoals, coral cover was highest on the back reef (18.8%) and lowest in the lagoon (7.7%; Kenyon et al., 2006b). The most northern reef systems in the NWHI (Pearl and Hermes, Midway, and Kure) are described as classic atolls, as their perimeter reefs more completely surround a central lagoon. Quantitative analysis of benthic video images recorded over extensive distances by towed divers between 2000 and 2003 indicates that, in these classic atoll geomorphologies, coral cover is highest in the lagoon at Pearl and Hermes (19.1%) and at Kure (18.6%) and on the back reef at Midway (6.4%; Kenyon et al., 2007a; 2008b). At all three locations, coral cover is lowest on the fore reef, ranging from 1.6% at Midway to 9.7% at Kure. Coral cover is low (5.3%) on the shallow (<30 m) bank surrounding Laysan (Kenyon et al., 2007b).

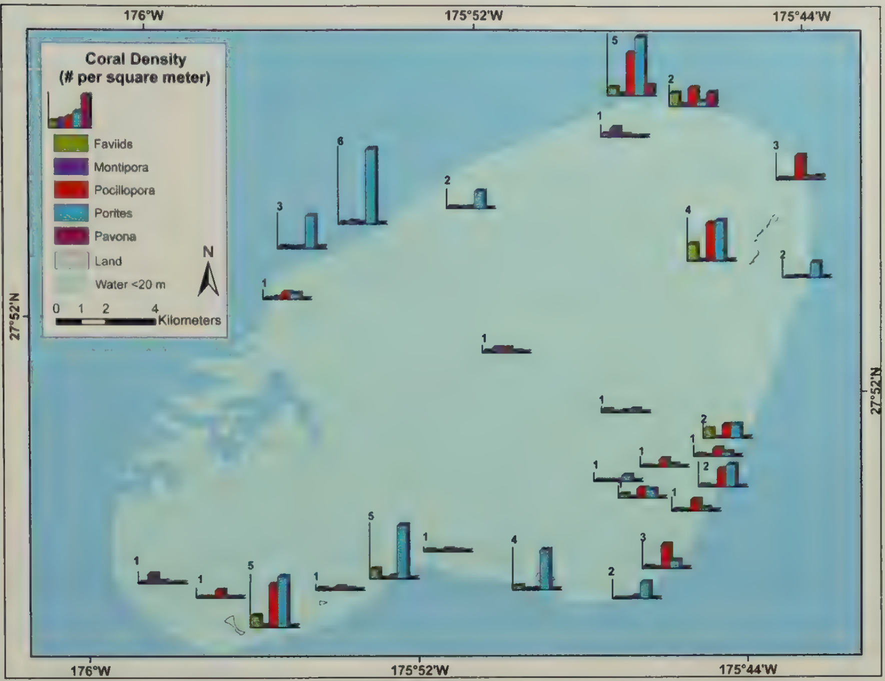


Figure 4.11. Colony density (n/m²) of five coral genera at Pearl and Hermes Atoll, NWHI. Number of colonies (n) was determined from belt transect surveys conducted in 2002. Source: NWHI RAMP; map, L. Wedding.

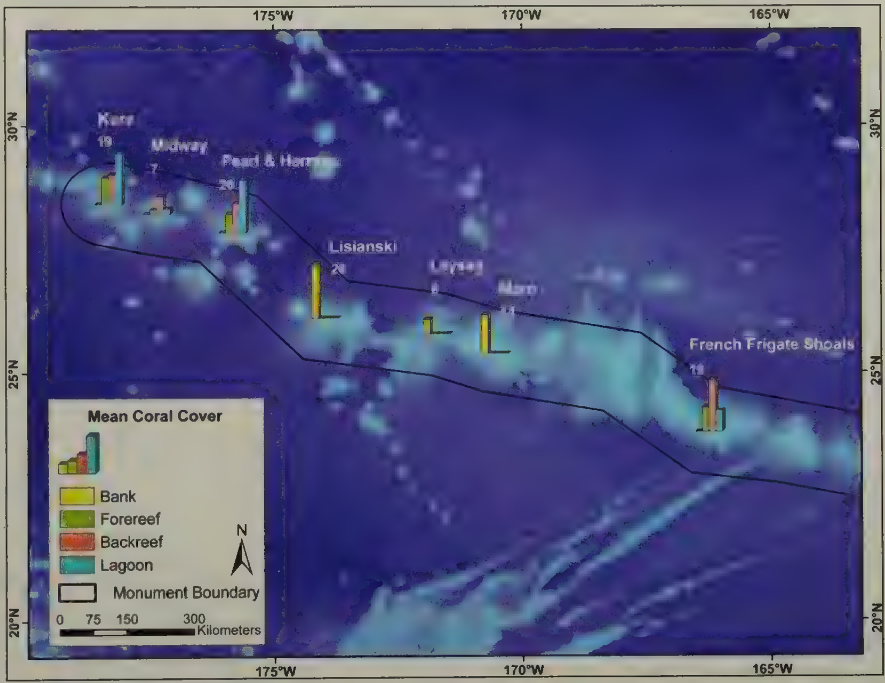


Figure 4.12. Differences in coral cover within different reef zones in the NWHI. Numbers represent the average coral cover: (%) + standard error. Coral cover calculated from size frequency data of colonies within transects. Data based on REA surveys in 2002. Not all habitats were sampled at all reefs. Source: NWHI RAMP, unpublished data; map: L. Wedding.

Wave exposure is a major determinant controlling the development of Hawaiian coral reefs, with moderate coral cover developing in areas directly exposed to winter wave regimes and high coral cover developing in sheltered embayments and areas protected from direct swells. In the NWHI, the greatest winter wave stress originates primarily from the northwest and secondarily from the northeast. At French Frigate Shoals, an open atoll lacking perimeter reef to the west, coral cover on the fore reef was highest in the northwest sector (approximately 26%; Kenyon et al., 2006b). At Pearl and Hermes Atoll, coral cover was highest on the fore reef in the northwest and north sectors (approximately 24–28%; Kenyon et al., 2007a). At Midway Atoll, coral cover on the fore reef was also highest on the north sector (J. Kenyon, unpubl. data). At Kure Atoll, coral cover on the fore reef was highest along the arc extending counterclockwise from north to west (approximately 11–16%; Kenyon et al., 2008b). At Laysan, coral cover was highest in the northwest sector (7.3%; Kenyon et al., 2007b). Reef-wide patterns of coral cover at Maro Reef and Lisianski vary from those at other locations in the NWHI with respect to wave exposure. At Maro Reef, an open atoll with no perimeter reef, the highest coral cover was along the northeast sector, closely followed by the southwest sector (Kenyon et al., 2008a). At Lisianski/Neva Shoal, an open atoll with limited perimeter reef, coral cover was highest in the southeast and southwest sectors (approximately 25–27%; Kenyon et al., 2007b). Both Lisianski/Neva Shoal and Maro Reef are classified as open atolls, but their complex structure of reticulate reef with little to no enclosure by perimeter reef likely generates a more complicated pattern of wave exposure than that experienced by atolls more clearly delineated by a perimeter reef, and accordingly they are characterized by different patterns of highest coral cover.

Wave Action

High – north and west sectors experience regular large to huge wave events, especially in winter months where waves can exceed more than 15 m in height. Primary benthic components on exposed reefs are energy tolerant species and growth forms such as crustose coralline algae, non-delicate fleshy algae and encrusting *Porites* corals.

Medium – east sectors experience nearly constant moderate wave action due to exposure from trade wind generated swells. Southern exposures receive occasional large swells generated by storms of tropical origin, especially in summer months.

Low – the southwesterly parts of the islands generally represent the most protected sectors of the islands, but this generally applies to larger islands/atolls where shelter from waves is more extensive. Areas of shelter are minimal for the smaller islands. Atoll lagoons are the most protected of all geomorphological zones of the NWHI.

Although early work in the NWHI assumed the best developed seaward reefs would occur off southwestern coasts (Grigg, 1983), analysis of imagery from more extensive and spatially comprehensive towed-diver surveys indicate coral cover on the fore reef is highest along the northwest, north, or northeast sectors at French Frigate Shoals, Maro Reef, Laysan, Pearl and Hermes Atoll, Midway Atoll, and Kure Atoll (Kenyon et al., 2006b; 2007a,b; 2008a,b). Only at Lisianski/Neva Shoal is coral cover highest along the southwest sector (Kenyon et al., 2007b) .

Effects of Temperature on Northwestern Hawaiian Island Corals

The coral reefs of the NWHI are in sub-tropical latitudes and exposed to large seasonal temperature fluctuations, particularly Kure, Midway and Pearl and Hermes Atolls, at the northwestern end of the archipelago. Sea surface temperature (SST) at these northerly atolls can fluctuate from less than 18°C in late winter (17°C in 1997) to highs exceeding 28°C in the late summer months (29°C in 2002). Compared with most reef ecosystems around the globe, the annual fluctuations of SST of 10°C at these northerly atolls is extremely high. The cooler winter temperatures are thought to reduce coral growth rates. While the summer temperatures are generally similar along the entire NWHI, the warmest summer temperatures tend to occur at the three northernmost atolls, presumably caused by reduced mixing due to weaker winds (situated closer to the center of the North Pacific high pressure ridge) and decreased circulation due to large shallow water lagoons (Brainard et al., 2004; Hoeke et al., 2005). Roughly two-thirds of the variability in growth rate across the archipelago can be explained by changes in temperature and light availability (Grigg, 1982). Growth rates for a representative species of coral *(P. lobata*) dominant throughout the chain vary from 3 mm/yr to 13 mm/yr (Grigg, 1982).

Siciliano (2005), however, reports that, while coral growth rates generally decline as a function of increasing latitude in the NWHI, as originally suggested by Grigg (1982), this decrease is habitat-specific. Coral colonies found in protected habitats throughout the NWHI chain (i.e., back reef and lagoon habitats on the atolls; embayments sheltered from wave action at the islands lacking lagoons) grow at similar rates regardless of latitude. This is may be explained by the microclimatic conditions experienced by corals growing in the shallower lagoon and back reef habitats, which are not closely related to offshore SST (Jokiel and Brown, 2004). Growth rates in these habitats may be influenced more by light and competition for space with other corals than by the relatively stable, and sometimes higher ambient temperatures afforded by these protected environments from solar heating in shallower lagoons. Conversely, corals growing in exposed habitats throughout the NWHI (i.e., fore reef of atolls or the reef slope of islands lacking a lagoon) experience temperatures more akin to offshore SST conditions, and therefore are more likely to respond to regional SST gradients, such as decreasing SST with increasing latitude, resulting in the measured latitudinal decrease in growth rates in these habitats.

The growth rates reported by Grigg (1982) may also be an under-estimate at Kure Atoll because of selective sampling. In his assessment of coral growth rate throughout the NWHI, Grigg (1982) sampled *Porites lobata* exclusively in 10 m depth from exposed southwest areas. Inspection of *Porites*' growth rates in three habitats at Kure atoll (Table 4.6, from Siciliano, 2005) reveals that the fore reef has the lowest growth rate

Table 4.6. Mean linear growth rates (cm/yr) of five main reef-building coral genera in three habitats at Kure Atoll. Source: Siciliano, 2005.

GENUS	FORE REEF	BACK REEF	LAGOON
Porites	0.45	0.74	1.01
Pocillopora	1.69	1.72	1.69
Montipora	0.10	0.10	0.12
Pavona	1.63	0.76	0.63
Leptastrea	0.20	0.22	0.24

for this genus, among all sites sampled. Therefore exclusive sampling from this area is likely to underestimate average growth rates per atoll. Even so, *Porites*' growth rates from the fore reef habitat in Siciliano's study (4.5 mm/yr) are higher than those reported by Grigg for *Porites lobata* (3 mm/yr), even if the data for Porites exclude the faster growing, branching forms such as *P. compressa* (largely absent from Kure's fore reef). Encrusting and more massive growth forms of *P. lobata* and *P. evermanni*, important reef builders at Kure, were included in the more recent assessment.

Inspection of Table 4.6 also indicates that if the *Porites* growth rates were adjusted to reflect those of other reef-building corals in the fore reef habitat using Grigg's approach (i.e., by averaging *Porites*' growth rates with those of other reef-building genera), the corals' growth rate would increase to 0.8 mm/yr, rather than decrease as suggested by Grigg (1982), who reported an adjusted growth rate of 0.2 mm/yr for Kure Atoll.

Monitoring Corals at Permanent Transect Sites in the Northwestern Hawaiian Islands: 2001-2006

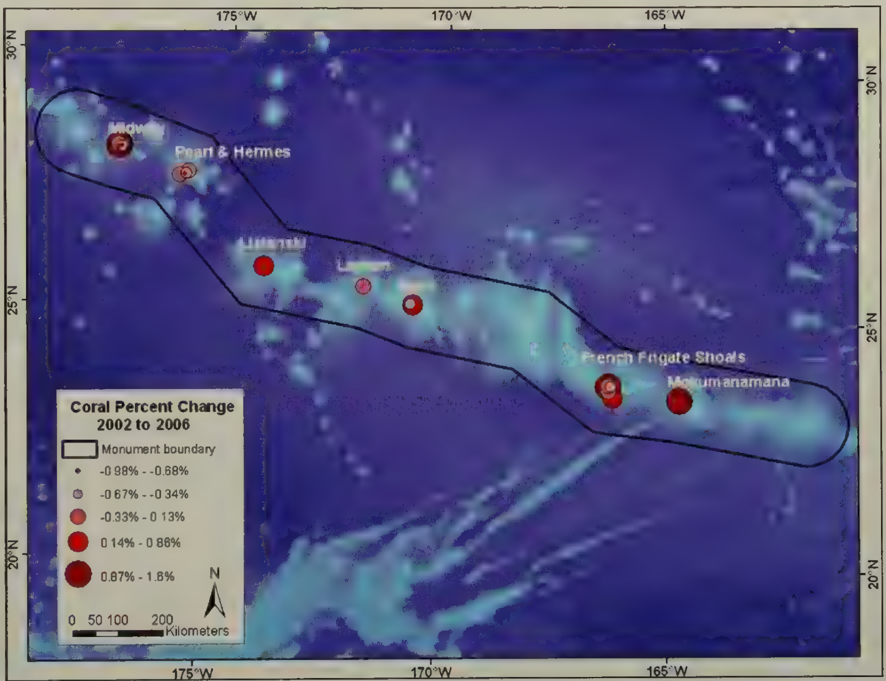


Figure 4.13. Percent change in coral cover between 2001-2002 and 2006 at permanent stations in the PMNM. Source: Maragos, unpub. data; map: L. Wedding.

This section focuses on the results of monitoring coral communities at 27 permanently marked transects established at seven of the 10 NWHI from 2001-2002 and resurveyed in September 2006, and account for most of the 42 permanent transects established in the NWHI from 2000-2002. Changes in percent coral cover per transect were compared between 2001-2002 and 2006 at permanent transects (Figure 4.13). Mean coral cover declined by 2% from 2001-2002 to 2006 but was not significantly different between these time periods (w= 53, p=0.51). Table 4.7 summarizes the results of the 2006 permanent transect resurveys and offers a comparisons to earlier surveys at the same sites. The changes in percent coral cover, mean diameter, number of coral genera and the density of all corals per transect are provided in the table. When pooling the data for all 27 sites, percent coral cover declined from 16.6 % to 14%, mean diameter declined from 22.7 to 15.5 cm, number of genera increased from 2.9 to 4.3, and coral densities increased from 4.8 to 6.7 corals m^2 at the same set of transect sites over the four to five year interval. These trends are significant for all categories except percent coral cover. Changes in the survey techniques between the two sets of surveys can explain some of these patterns. For one, *in situ* census of corals vis-à-vis analysis of photos would likely lead to detecting greater numbers and genera for smaller corals, leading to lower mean diameter values. However, the analysis of the individual sites over the time interval reveals that some of these trends can only be explained by *in situ* observations and site-specific data.

Table 4.7. Percent coral cover, mean diameter, number of genera and frequency of all corals at each of 27 permanent transect sites surveyed in 2001-2002 and 2006. Bold numbers are the higher of two (earlier or later) values at each site.

SITE NUMBER	**HABITAT**	**LOCALE**	**DATE**	**PERCENT CORAL COVER**		**MEAN DIAMETER CM**		**NUMBER GENERA/SITE**		**DENSITY (#/m²)**	
				2001-2002	**2006**	**2001-2002**	**2006**	**2001-2002**	**2006**	**2001-2002**	**2006**
FFS- 5P	fore reef	NW	7/17/2001	**19.4**	16.8	11.6	**13.3**	**4**	3	**14.2**	11.7
FFS 3P	lagoon basalt	N cen.	7/16/2001	27.7	**28.8**	**19.9**	17.8	5	5	8.5	**11.5**
FFS 16P	Lagoon	N	9/15/2001	4.8	**9.5**	12.3	**15.1**	**5**	4	4.6	**7.8**
FFS 2P	reef crest	S	7/15/2001	27.2	**33.5**	**26.2**	20.1	**7**	6	5.3	**9.4**
FFS 11P	back reef	N	10/30/2002	**39.1**	22	**76.2**	21.3	3	**4**	1.6	**5.9**
LAY 1P	channel	S	9/17/2001	**5.9**	5.1	7.7	**10.9**	3	**6**	**9.5**	4.9
LAY 5P	reef pool	SE	9/18/2002	7.7	**8.7**	11	**14.6**	3	**4**	**5.6**	4.8
LIS 1P	reef crest	S cen.	9/30/2002	**5.3**	0.43	**14.5**	4.6	2	**4**	**3.8**	0.36
LIS 9P	pinnacle	E	10/2/2002	19.2	**24.9**	**22.9**	16.3	2	**4**	5.1	**9.8**
LIS 6P	fore reef	N	10/1/2002	27.9	**46.8**	**57.4**	40.6	1	**3**	1.8	**4**
MAR 4P	back reef	NW	9/16/2002	**52**	34.4	**36.4**	20.6	3	**7**	6.4	**11.4**
MAR 5P	Lagoon	center	9/21/2001	4.2	**5.9**	**10.9**	10.3	2	**5**	3.8	**5.1**
MAR 1P	fore reef	SE	9/15/2002	**32.4**	7.9	**29.6**	9.3	3	**7**	4.6	**8.2**
MID 7P	Lagoon	E	9/23/2002	**50**	1.1	**25**	7.6	4	4	nd.	3.2*
MID 16P	back reef	N	12/3/2002	24.3	**36**	**46.7**	29.7	3	3	2.1	**5.8**
MID 14P	lagoon pinnacle	center	9/24/2002	4.7	**12.2**	8	**12**	2	**3**	**12.2**	9.5
MID 18P	back reef	NE	12/4/2002	0.7	**1.3**	6.8	**7.4**	4	**5**	2.5	**3.5**
MID 19P	lagoon pinnacle	SW	12/5/2002	**5.1**	0.9	**14.7**	13.1	2	**3**	**2.77**	1.02
MID 20P	back reef	NW	12/6/2002	**22.3**	19.2	**48.7**	31	**3**	2	1.46	**2.7**
MID 1Pa	reef crest	E	12/3/2002	**3.3**	1.04	**17.6**	11.7	2	**4**	1.73	**2.46**
MID 2P	back reef	NE	9/21/2002	13.8	13.8	**22.6**	21.3	4	4	2.8	2.8
MID 17P	back reef	E	12/4/2002	**9**	3.5	10.4	**20**	2	**4**	**4.6**	1
MMM 1P	basalt fore reef	S	9/9/2002	6	**14.6**	8.4	**10.6**	2	**4**	9.1	**18.4**
PHR 6P	lagoon pinnacle	S	9/19/2002	**2.53**	1.53	**11.7**	7.6	2	**4**	1.8	**4.8**
PHR 7P	lagoon patch reef	center	9/27/2002	**24**	20.7	**25.6**	10.1	1	**3**	**4.64**	19.8
PHR 9P	Pass	S	9/28/2002	**1.69**	0.23	**14.4**	9.5	2	**4**	**1.07**	0.4
PHR12P	fore reef	SW	9/29/2002	**8.95**	7.11	**15.5**	11.1	3	**6**	3.15	**6.48**
TOTALS	**27**		**MEANS**	**16.64**	14	**22.69**	15.46	2.9	**4.3**	4.8	**6.7**

Mokumanamana

Permanently marked transect NEC-1P is located in a semi-sheltered recessed bay or bight off the southwest side of Mokumanamana and is the only permanent transect established to date. The site was re-surveyed on September 3, 2006. All coral population parameters increased during the four year period between the two surveys. Mean diameter increased from 8.4 cm to 10.6 cm. Coral densities increased from 9.1 to 18.4/m^2, generic diversity increased from two to five genera, and coral cover more than doubled to 14.6%. All four of the smaller size classes for total corals increased substantially during the four year period although there were only a few corals represented at the higher size classes for each survey period (Figures 4.14 and 4.15). Overall, all smaller size classes increased and the larger stayed the same. Severe exposure to waves from any direction and the large winter swell from the northwest may prevent development of large, high profile corals. The lobe coral (*Porites lobata)* followed by the rose/cauliflower coral (*Pocillopora meandrina)* continue to dominate the coral fauna, although the zoanthid soft coral (*Palythoa tuberculosa)* has emerged as a common coral on the transect in 2006, even though absent in 2002. The number of *Porites* corals doubled for the all four smaller size classes while *Pocillopora* also increased dramatically in all size classes. Despite the exposed and scoured environment at the site, corals have increased dramatically at NEC-1P over the four year period.

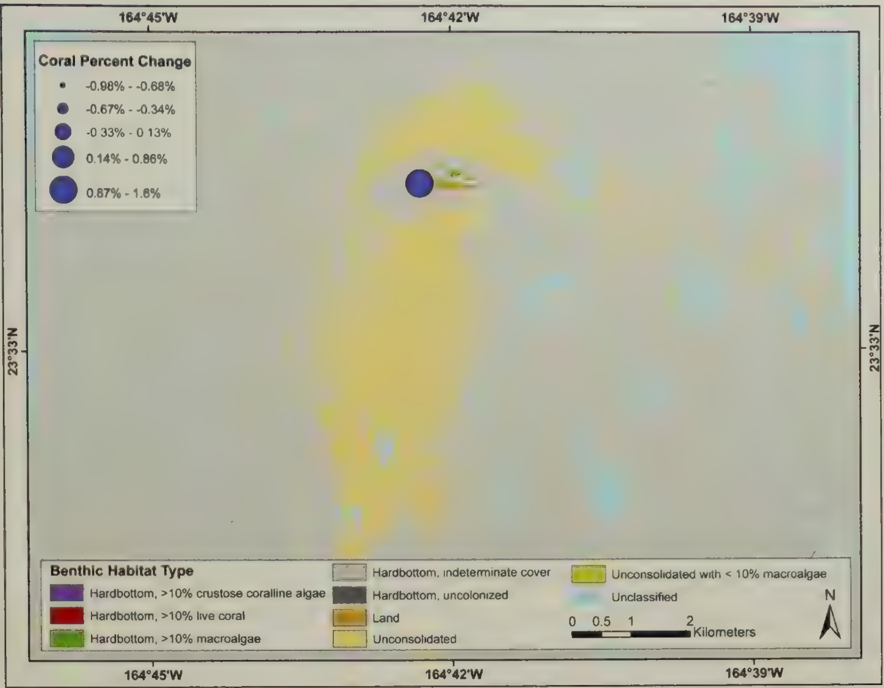


Figure 4.14. Percent change in coral cover at Mokumanamana between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

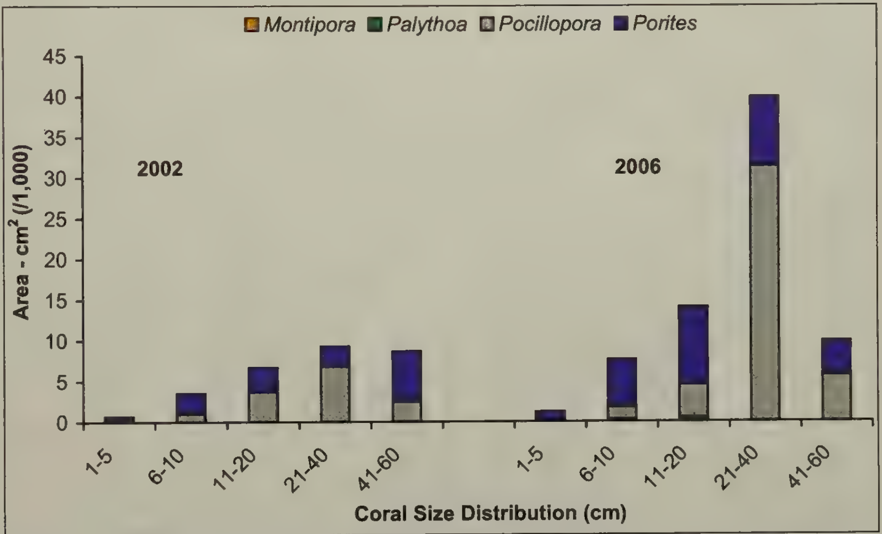


Figure 4.15. Changes in the proportion of each genus, size distribution and cover for corals reported at Mokumanamana Island permanent sites between 2001-2002 and 2006 permanent site 1P. Source: Maragos, unpub. data.

French Frigate Shoals

Eleven permanent monitoring transects for corals were established at French Frigate Shoals from 2001-2002, with four resurveyed in September 2006. These are: Serendipity Hollow (site FFS 11P) on the northern back reef; site FFS 16P at the CREWS buoy site in the northern lagoon; site FFS 3P off the north side of La Perouse Pinnacle in the north central lagoon; and site FFS 2P just west of Disappearing Island off the south reef crest of the atoll. Large northerly swell and limited time during the visit prevented safe access to and survey of the remaining seven sites.

All sites showed increases in coral density (number of corals/m^2) and most showed increases in coral cover and generic diversity (Figures 4.16 and 4.17). The northern lagoon site (FFS-16P) showed increases in mean coral diameter and dramatic increases in the other coral parameters between 2001 and 2006, although the three smallest size classes peaked in 2002. The Serendipity Hollow (FFS 11P) site appears to have experienced wave damage in the recent past, based upon broken and overturned corals observed at the site in 2006, but coral populations continued to maintain high values and post modest increases in all size classes except the largest two. The La Perouse site (FFS 3P) posted increases in generic richness, with the addition of *Acropora, Montipora and Psammocora*, although there were slight decreases in the abundance of *Pocillopora* and *Porites*. Corals at the Disappearing Island, site (FFS 2P) showed consistent gains in the four smallest size classes and dramatic increases in the number of genera over the five year period. Moreover, six coral genera noticeably increased in abundance (*Acropora, Pocillopora, Porites, Palythoa, Pavona, Psammocora*) with *Montipora* showing a modest decline.

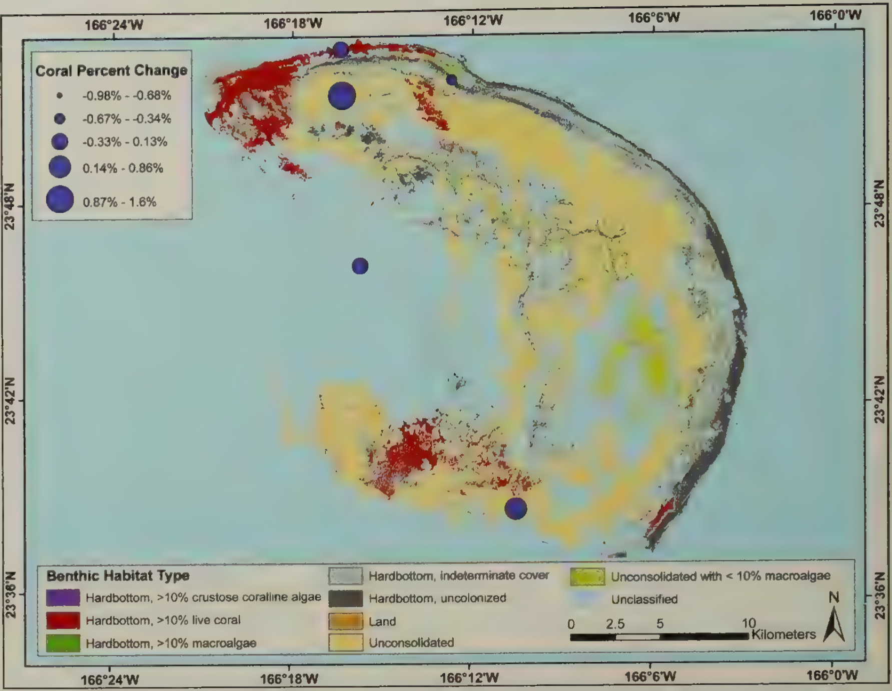


Figure 4.16. Percent change in coral cover at French Frigate Shoals between 2002 and 2006. Source: Maragos unpub. data; map: L. Wedding.

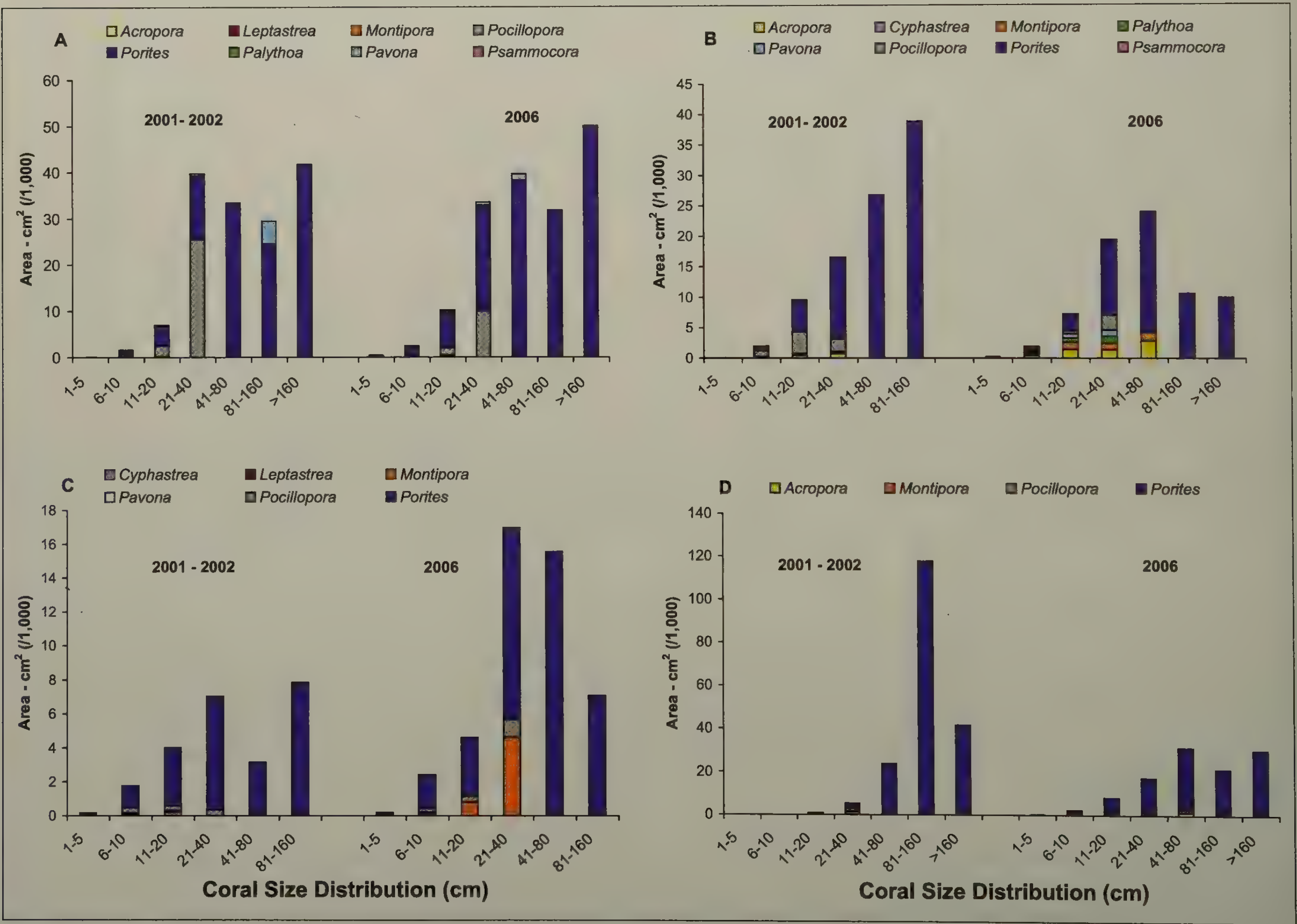


Figure 4.17. Changes in the proportion of each genus, size distribution and cover for corals reported at French Frigate Shoals permanent sites between 2001-2002 and 2006: a) 2P, b) 3P, c) 16P and d) 11P. Source: Maragos, unpub. data.

Maro Reef

Three permanent transect sites were established at Maro Reef between September 2001 and September 2002 (Figures 4.18 and 4.19). Site MAR 1P is located on a southeast facing fore reef of a patch reef. Site MAR 4P is located at the far northwest end of Maro, on a south-facing leeward fore reef. MAR 15P is near the middle of these two extremes in the central shallow protected lagoon 20 m north of the NOAA CREWS buoy. All sites were resurveyed on 7-9 September 2006. Wave exposure varies considerably among the three, with the southeast site most exposed, the central site least exposed, and the northwest subjected to intermediate wave but stronger current exposure.

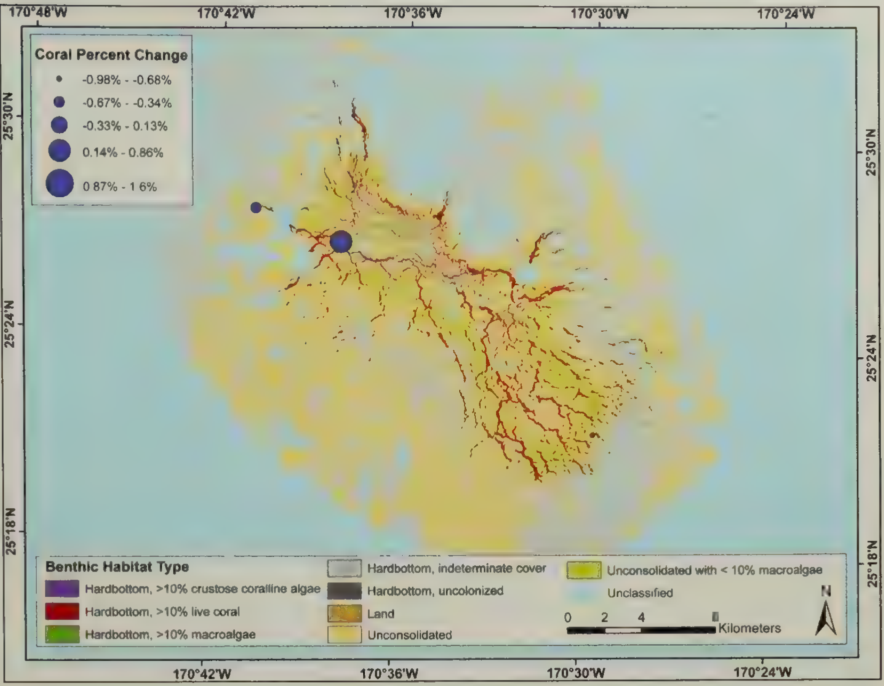


Figure 4.18. Percent change in coral cover at Maro Reef between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

Coral populations showed mixed trends over the four to five year period. The number of genera increased from 2-3 per site in 2001-2002 and to 6-7 per site in 2006. The dominant corals at all three transects were the lobe coral (*Porites lobata)* and the rose coral (*Pocillopora meandrina).* Other common coral genera were *Pavona* and *Montipora,* the latter absent at the southeast site in 2001 (MAR 1P), but more abundant at all three in 2006. The encrusting brain coral (*Leptastrea pruinosa)* was absent at all three sites in 2001-2002 but emerged as a common species at the northeast site (MAR 4P).

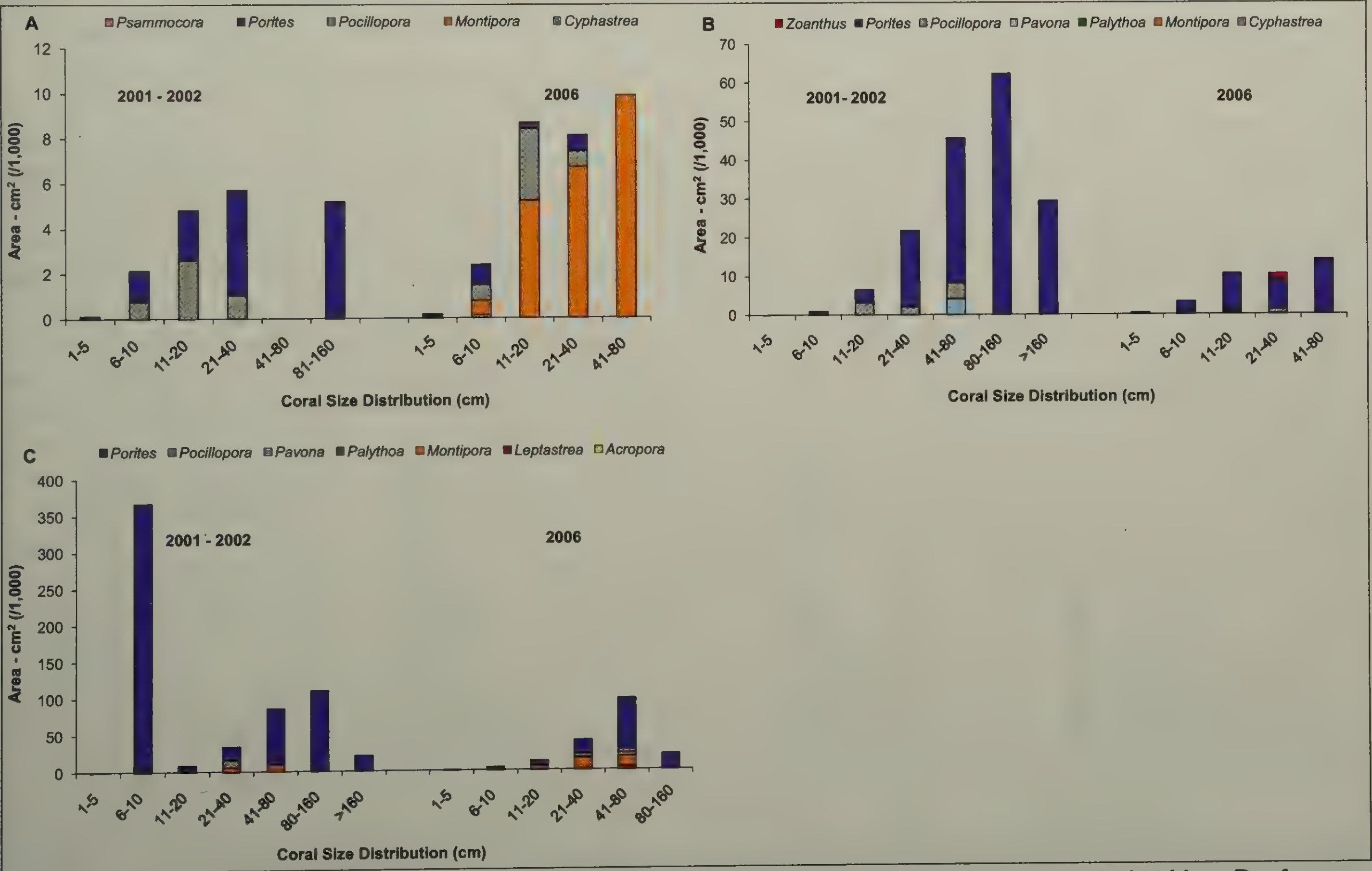


Figure 4.19. Changes in the proportion of each genus, size distribution and cover for corals reported at Maro Reef permanent sites between 2001-2002 and 2006: A) 15P, B) 1P and C) 4P. Source: Maragos, unpub. data.

Mean diameters decreased at all sites, from 10.9, 29.6 and 36.5 cm in 2001-2002 to 10.3, 9.3 and 20.6 in 2006 at sites MAR 1P, MAR 4P and MAR 15P, respectively. However, coral densities (number of corals/m^2) increased at all sites over the same period from 3.8, 4.7 and 6.4 to 5.1, 8.4 and 11.2 corals in 2006 at the same respective sites. Coral cover decreased at MAR 4P and 1P and increased at MAR 15P. At site MAR 15P the numbers of smaller corals generally increased, but at the southeast site (MAR-1P) and the northwest site (MAR 4P) the numbers for all size classes decreased. Many larger corals appeared to show signs of fragmentation to smaller sized corals at the two more exposed sites (MAR-1P, MAR-4P) that could explain the observed shifts in size.

Laysan Island

Two permanent transect sites were established at Laysan Island in September 2002 and resurveyed in September 2006. Site LAY-1P is located along the north side of the sand channel in the southwest embayment (Figures 4.20 and 4.21). Site LAY-5P is located on the shallow southwest reef crest, just south of the embayment and west of the NOAA monitoring buoy. Both transects are sheltered from heavy winter swells from the northwest Pacific that strike the NWHI during the winter months.

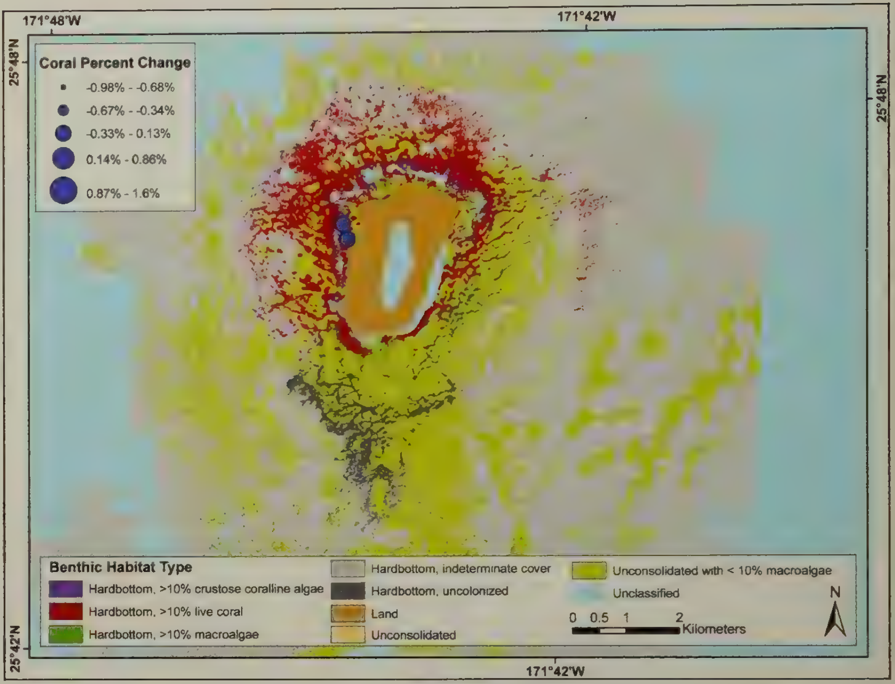
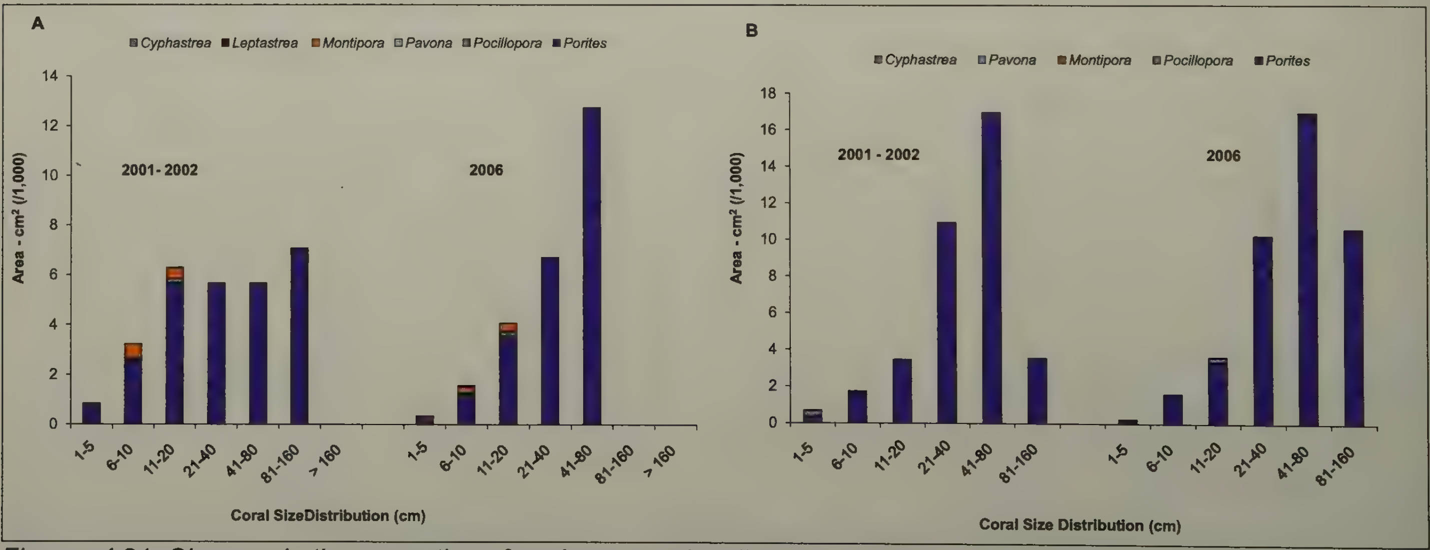


Figure 4.20. Percent change in coral cover at Laysan Island between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

Coral population parameters showed mixed trends over the four-year period. Generic richness increased from three to four genera at sites LAY-1P and LAY-5P from 2002-2006. Mean diameters also increased at both sites, from 7.7 cm to 10.9 cm at LAY-1P and from 11 cm to 14.7 cm at LAY-5. However, coral densities dropped at both sites, dramatically at LAY-1P from 9.5 to 4.9, and less so at LAY-5P from 5.6 to 4.8 over the four- ear period. About 10% of the corals, mostly *Porites lobata,* at LAY-1P appeared sick or dying, and overall coral health at this site appears less than reported there in 2002, including a 50% decrease in coral cover. There were few sick or dying corals at the reef crest site LAY-5P although coral cover declined slightly.



Figures 4.21. Changes in the proportion of each genus, size distribution, and cover for corals reported at Laysan Island permanent sites between 2001-2002 and 2006: A) 1P B) 5P. Source: Maragos, unpub. data.

Laysan's smaller oval shape renders it vulnerable to severe exposure to waves from the west to northeast, and the large winter swell from the northwest may prevent development of large, high profile corals at shallow depths. Although not measured during the 2006 surveys, benthic algal cover appeared especially high at the west channel site LAY-1P, and algae is prolific at other sites (J. Maragos, per. obs.). Aside from its small size, Laysan Island supports over a million breeding seabirds and significant monk seal and sea turtle populations. Together with seepage from its high nutrient-laden hypersaline lake, Laysan Island may be subsidizing substantial localized productivity from local nutrients which in turn may favor the growth of algae over corals in most shallow reef habitats.

Lisianski Island

Three permanent 50 m long transects were established in shallow water near Lisianski Island in September-October 2002 and all three were resurveyed in September 2006 (Figures 4.22 and 4.23). Site LIS 1P was established on the shallow southwest fore reef at depths of 1.2 to 4.6 m. Site LIS 6P was established near the opposite, east side of the island at similar depths along the fore reef-reef crest margin. The third site LIS 9P was established off the northern fore reef slope of the island at depths of 7.3-14.9 m. Water visibility, wave action and currents are notably stronger at the latter two sites (LIS 6P and 9P) located windward of the island. Site LIS 1P is down-drift of the island and in the direct path of current and water flow from the island.

In 2002 coral coverage was estimated at 5.3%, coral density at 3.8 corals/m², and mean diameter at 14.5 cm at the southwest site LIS-1P. Corals there were primarily plates of *Montipora* corals intermixed with green algal growths of *Neomeris* and *Microdictyon*. On the opposite, eastern site, LIS-6P, large plates of the same coral *Montipora* cf.

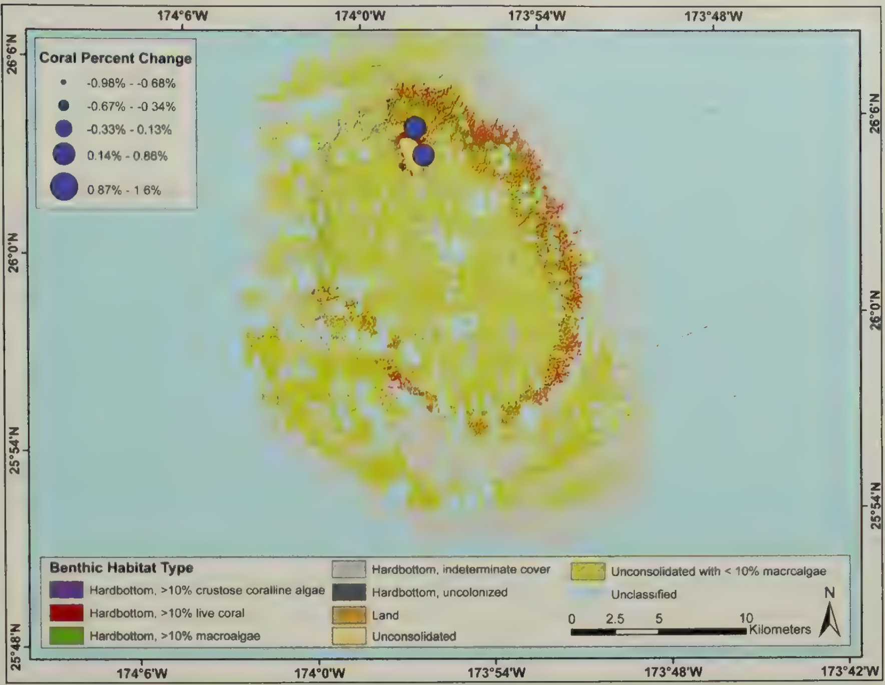


Figure 4.22. Percent change in coral cover at Lisianaski-Neva Shoals between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

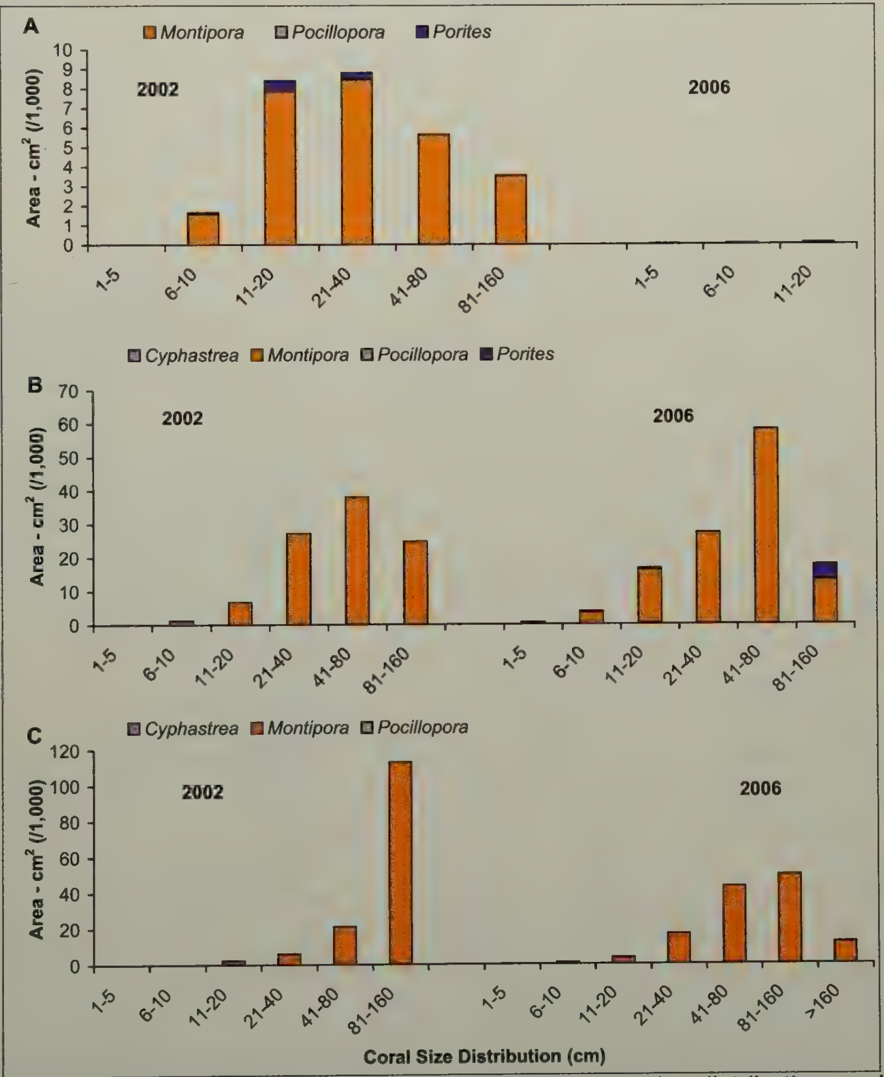


Figure 4.23. Changes in the proportion of each genus, size distribution, and cover for corals reported at Lisianski-Neva Shoals between 2002 and 2006: A) 1P, B) 9P and C) 6P. Source: Maragos, unpub. data.

turgescens dominated the bottom, averaging 27.9% coral cover, 1.8 corals/m^2, and with an average diameter of 57 cm in 2002. The north, offshore site consisted of hard bottom covered with encrusting *Montipora corals* at shallow (6-7.6 m) depths and transitioned to larger, widely spaced colonies of *Porites* lobe corals and *Pocillopora* rose corals over a rubble sand bottom at depths of 9.1-15.2 m. Coral coverage was 19.2% with a mean diameter of 23 cm and frequency 5.06 corals/m^2 in 2002.

Four years later, resurveys yielded a near total collapse of corals at site LIS-1P. Coral cover was estimated at 0.43%, mean diameter at 4.56 cm, and coral density at 0.36 corals/m^2, translating to only 17 corals in the three smallest size classes for the entire transect. In great contrast, the two windward sites fared much better over the four years with coral cover higher at both in 2006. Mean diameter at site LIS-6P was less but still substantial at 40.6 cm. Likewise site LIS-9P showed smaller mean diameter for corals at 16.3 cm, but coral frequencies nearly doubled at both windward sites, with 2006 values at 4.00 and 9.84 corals/m^2 respectively. The small brain coral *Cyphastrea* appeared at all three sites for the first time in 2006, and *Pocillopora* increased in size and numbers at all three sites. The plate coral *Montipora* nearly disappeared by 2006 at site LIS-1P with only 10 small colonies remaining from 184 mostly larger colonies in 2002. At the other two sites *Montipora* plate coral increased dramatically for smaller to middle sized corals. The lobe coral *Porites* also declined at the southwest site LIS-1P, but increased modestly at the northern site LIS-9P. Figure 24 illustrates the changes in size distribution for all corals over the four year period at the three sites.

The collapse of the coral community at southwest site LIS-1P may have been caused by a coral bleaching event followed by the overgrowth of algae, the latter perhaps stimulated by plentiful nutrients leaching from the island and derived by extensive guano production generated by the large resident seabird populations at Lisianski. Ambient water temperature was higher at the site during the 2006 survey and may have a longer residence time in shallow depths where solar heating would be higher. Also, the waters to the southwest were noticeably greener due to higher phytoplankton productivity. In contrast, water clarity was better, water motion stronger and temperatures cooler at the two windward sites that showed increased coral development.

Pearl and Hermes Atoll

Eight permanent coral transects were established at Pearl and Hermes prior to the September 2006 visit. Four of these were established at the site of the 2000 grounding of the fishing vessel *Swordman I*. The 2006 REA team did survey one or more of the back reef sites but these data are currently not available. The remaining four permanent transects established in 2002 consist of site PHR 6P, a shallow south lagoon pinnacle slope; PHR 7P, a central lagoon patch reef in the finger coral gardens; PHR 9P on the floor of the main south pass of the atoll; and PHR-12P off the southwest fore reef of the atoll (Figures 4.24 and 4.25).

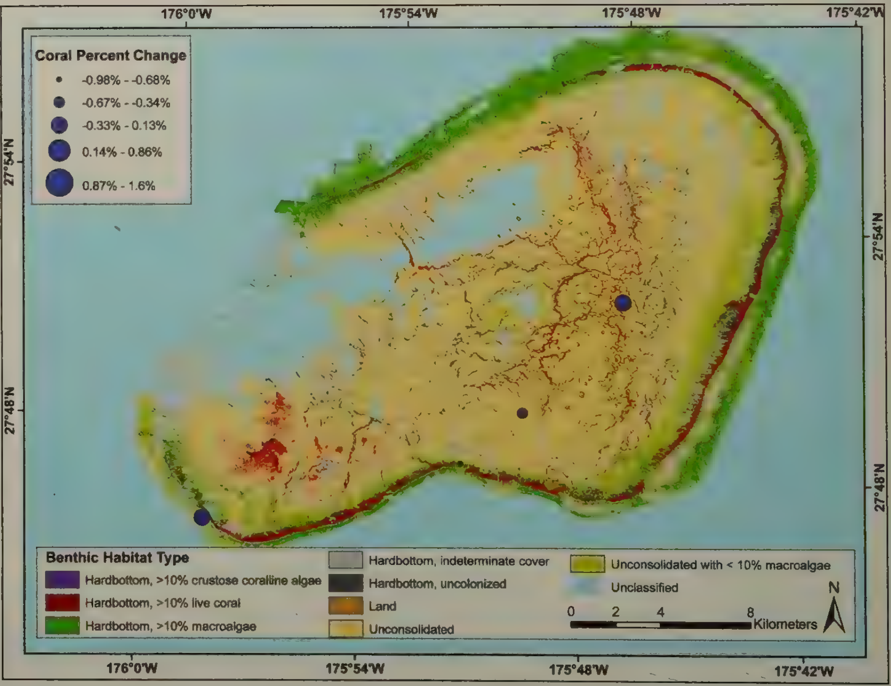


Figure 4.24. Percent change in coral cover at Pearl and Hermes Atoll between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

Coral populations showed smaller mean diameters (7.6 to 11.1 cm) in 2006 compared to their corresponding 2002 values (11.7 to 25.7 cm) at all sites. However, all sites showed higher generic diversity levels in 2006 (three to six genera/transect) compared to corresponding 2002 values (one to three genera). The 2006 coral populations also showed larger densities at all sites except PHR-9P, varying from 0.4 to19.8 corals/m^2, compared to 2002 levels (1.07 to 4.64 corals/m^2). The small brain coral (*Cyphastrea ocellina)* was reported on three transects for the first time in 2006, and *Palythoa, Pavona* and *Psammocora* were all reported for the first time on one transect each.

The three smallest size classes dominated the coral numbers at all 2006 sites except the south pass site (PHR-9P). Coral populations in the pass were much diminished from their 2002 levels at all size classes. During both the 2002 and 2006 surveys, currents ranged from 2 to 3 knots in the pass, with considerable suspended sediments. Scour and periodic wave action may be controlling coral development in the south pass. At the fingercoral garden site (PHR-7P), corals in the three smallest size classes were an order of magnitude more abundant in 2006 compared to 2002 levels for *Porites compressa*, although there was no substantial difference in the larger four size classes. In general, all corals combined were more numerous at the larger size classes at all four sites in 2002, Figure 4.25 compares size distributions for all corals in 2002 and 2006 at the four permanent coral transect sites.

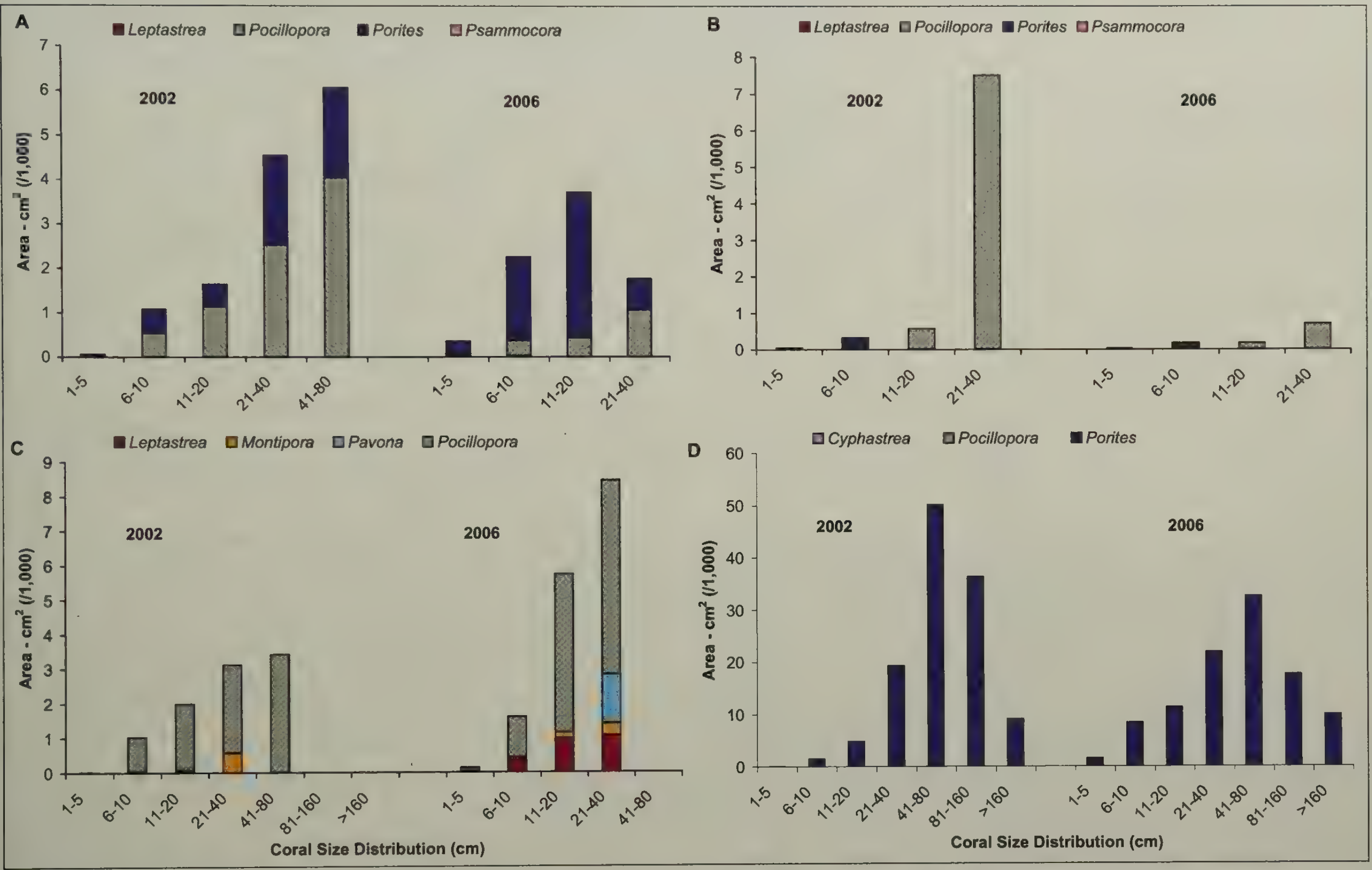


Figure 4.25. Changes in the proportion of each genus, size distribution, and cover for corals reported at Pearl and Hermes permanent sites 6P, 9P, 12P and 7P from 2002 and 2006. Source: Maragos, unpub. data.

Midway Atoll

Eleven permanently marked transects were established at Midway Atoll National Wildlife Refuge between 2000-2002. Eight sites were resurveyed in September 2006 and are shown in Figures 4.26 and 4.27. Five of the resurveyed sites are situated on the northern and eastern back reefs (MID 1Pa, 2P, 7P and 17P), two on the NW back reef (MID 18P, 20P), one near the southwest reef crest (MID 19P) and one on a central lagoon patch reef (MID 14P).

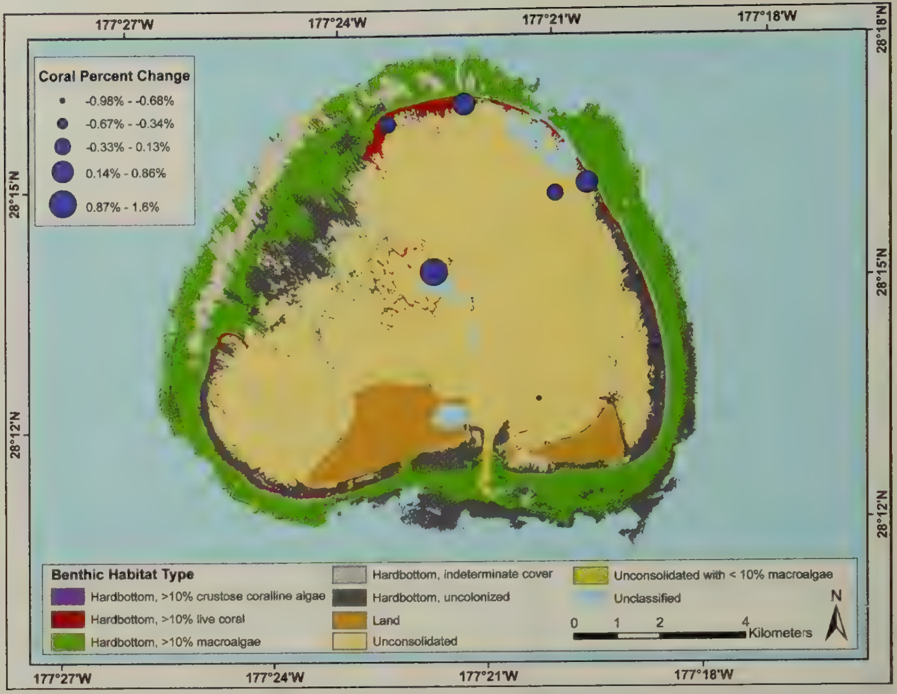


Figure 4.26. Percent change in coral cover at Midway Atoll between 2002 and 2006. Source: Maragos, unpub. data; map: L. Wedding.

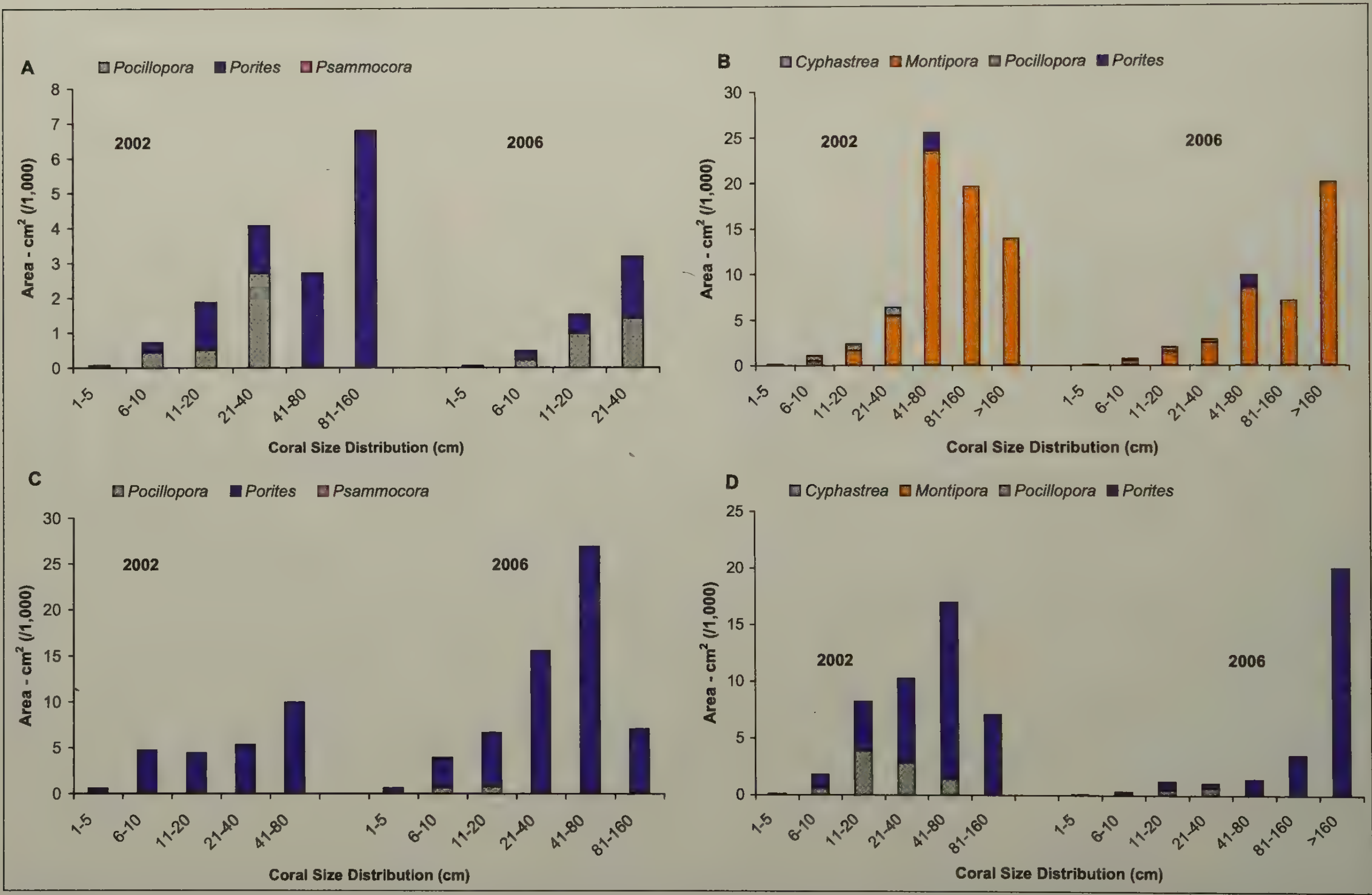


Figure 4.27. Changes in the proportion of each genus, size distribution, and cover for corals reported at 7 permanent sites at Midway: A) MID 1Pa, B) 2P, C) 14P, D) 17P, E) 18P, F) 19P and G) 20P. Source: Maragos, unpub. data.

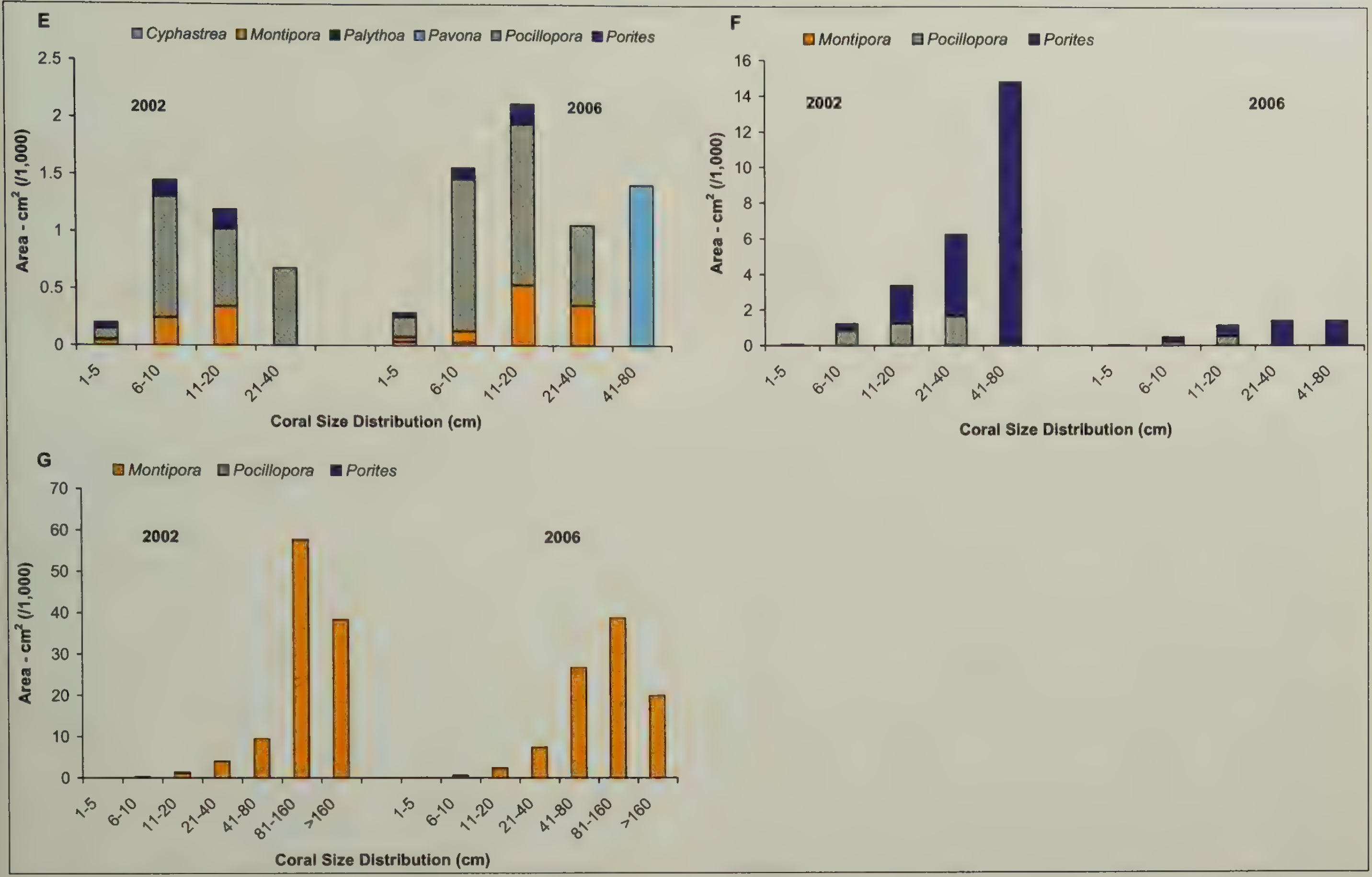


Figure 4.27 (continued). Changes in the proportion of each genus, size distribution, and cover for corals reported at 7 permanent sites at Midway: E) 18P, F) 19P and G) 20P. Source: Maragos, unpub. data.

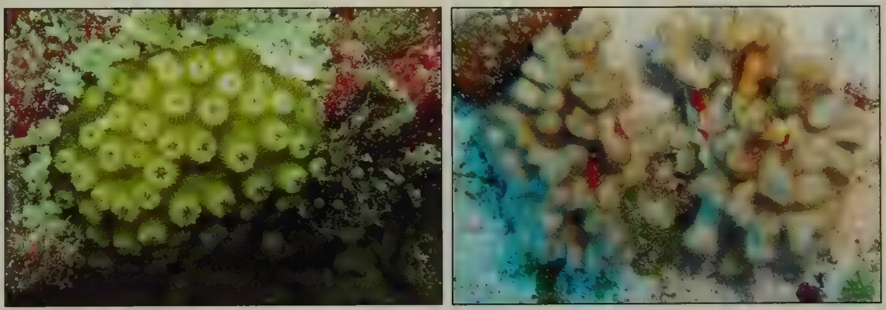


Figure 4.28. In 2006 both Cyphastrea ocellina *(left) and* Psammocora stellata *(right) were reported for the first time at Midway Atoll. Photos: J. Maragos.*

Overall, coral populations showed mixed trends during the four year period. The abundance and numbers of *Porites lobata* and *P. compressa* decreased slightly. The rose coral *Pocillopora* spp showed no clear trend, and the abundance of *Montipora capitata* and *M.* cf. *turgescens* generally increased from 2002-2006. The small brain coral (*Cyphastrea ocellina)* and small branching coral (*Psammocora stellata)* were reported for the first time at several transects in 2006 (Figure 4.28). Overall there were no trends for coral mean diameter or frequencies over the four year period, although generic diversity per transect increased at most sites.

The eastern back reef site MID-1Pa showed increases at smaller size classes but declines in larger corals. The neighboring east back reef site 17P showed major declines in all size classes and genera. Finger coral (*Porites compressa*) at the southeast lagoon site MID-7P were abundant in 2002, but in 2006 were all dead but still standing. The southwest reef crest/back reef site MID-19P also showed catastrophic declines in all corals. In contrast, the two northern back reef sites MID-20P and MID-18P dominated by *Montipora* showed major increases over the four year period. In 2002, *Montipora* at these sites were especially hit hard by coral bleaching, but now have rebounded to levels comparable if not higher than those reported earlier. The reasons for the major coral declines at sites MID-7P, -1P and -17P are not clear but warrant continued monitoring. The declines may be related to the residual effects of WWII and post WWII military construction at Midway, which resulted in the dredging of a deep channel between the lagoon and ocean and the likely change in lagoon circulation and water levels.

Descriptive Statistics for Corals from 2006 Rapid Ecological Assessment Data

Mokumanamana

In 2006 only two stations were sampled at Mokumanamana Island (Table 4.8, Figure 4.29). Average coral species richness ($\bar{x}$ = 11.5, SD ± 2.1) ranked the highest among all reefs surveyed. Percent live coral cover was 22.1% (SD ± 15.9) and ranked forth overall. Density of coral colonies (number/m^{-2}) also ranked first among all locations sampled in 2006 with a mean density of 6.9 colonies m^{-2}.

Table 4.8. Descriptive statistics for corals from 2006 REA data at Mokumanamana Island. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	2	11.5	2.12	1.5	-7.56	30.56
Coral cover (%)	2	22.06	15.94	11.28	-121.2	165.32
Density (no. m^{-2})	2	6.89	0.55	0.39	1.93	11.85

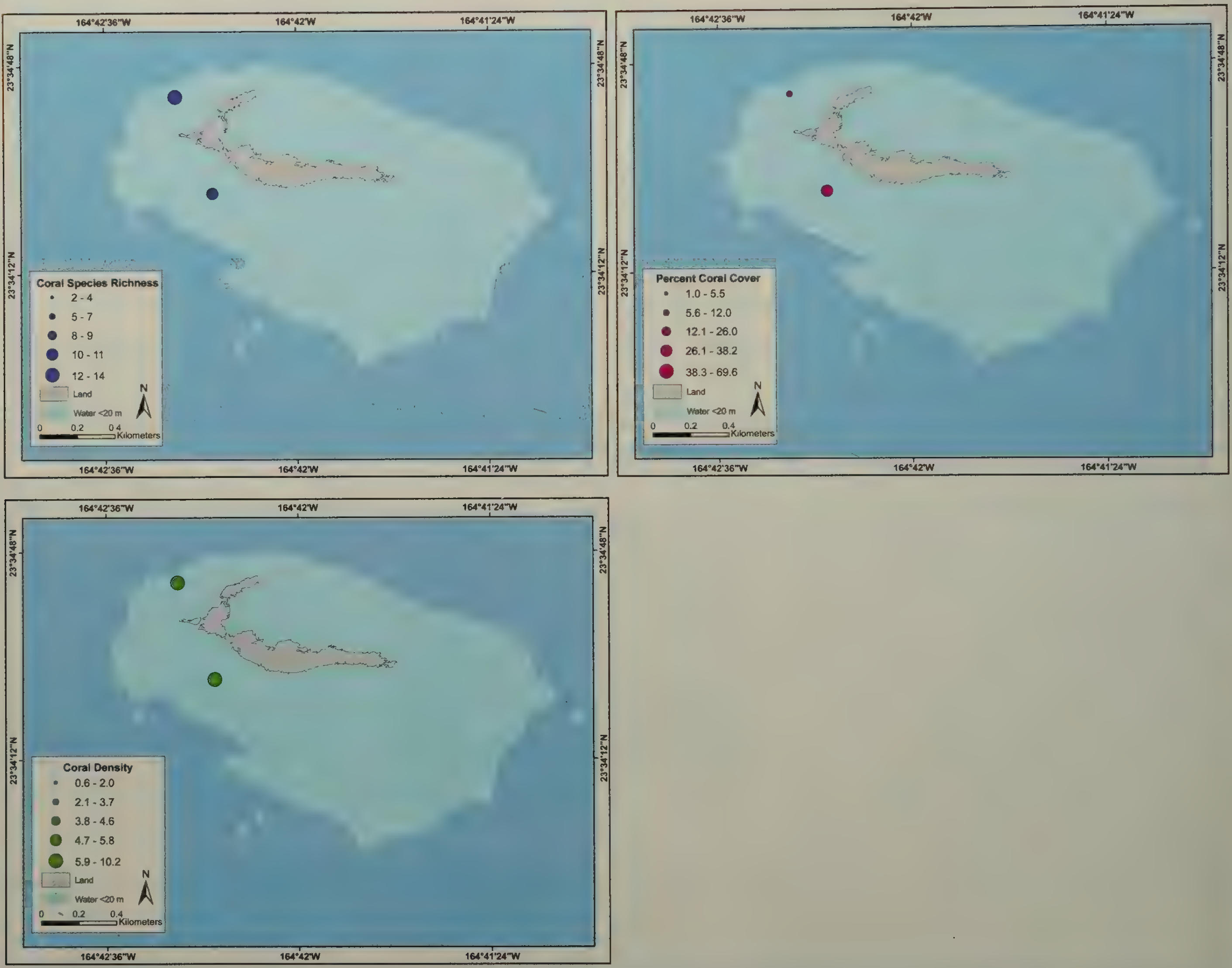


Figure 4.29. Mokumanamana coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

French Frigate Shoals

French Frigate Shoals ranked third overall in coral species richness with an average of 9.9 coral species per transect (Table 4.9, Figure 4.30). Percent live coral cover was 29.7% and also ranked third among all locations surveyed in 2006. Coral colony density was 4.82 m^{-2} and again ranked third among locations.

Table 4.9. Descriptive statistics for corals from 2006 REA data at French Frigate Shoals. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	10	9.9	3.07	0.97	7.7	12.1
Coral cover (%)	10	29.71	18.68	5.91	16.3	43.07
Density (no. m^{-2})	10	4.82	2.37	0.75	3.12	6.52

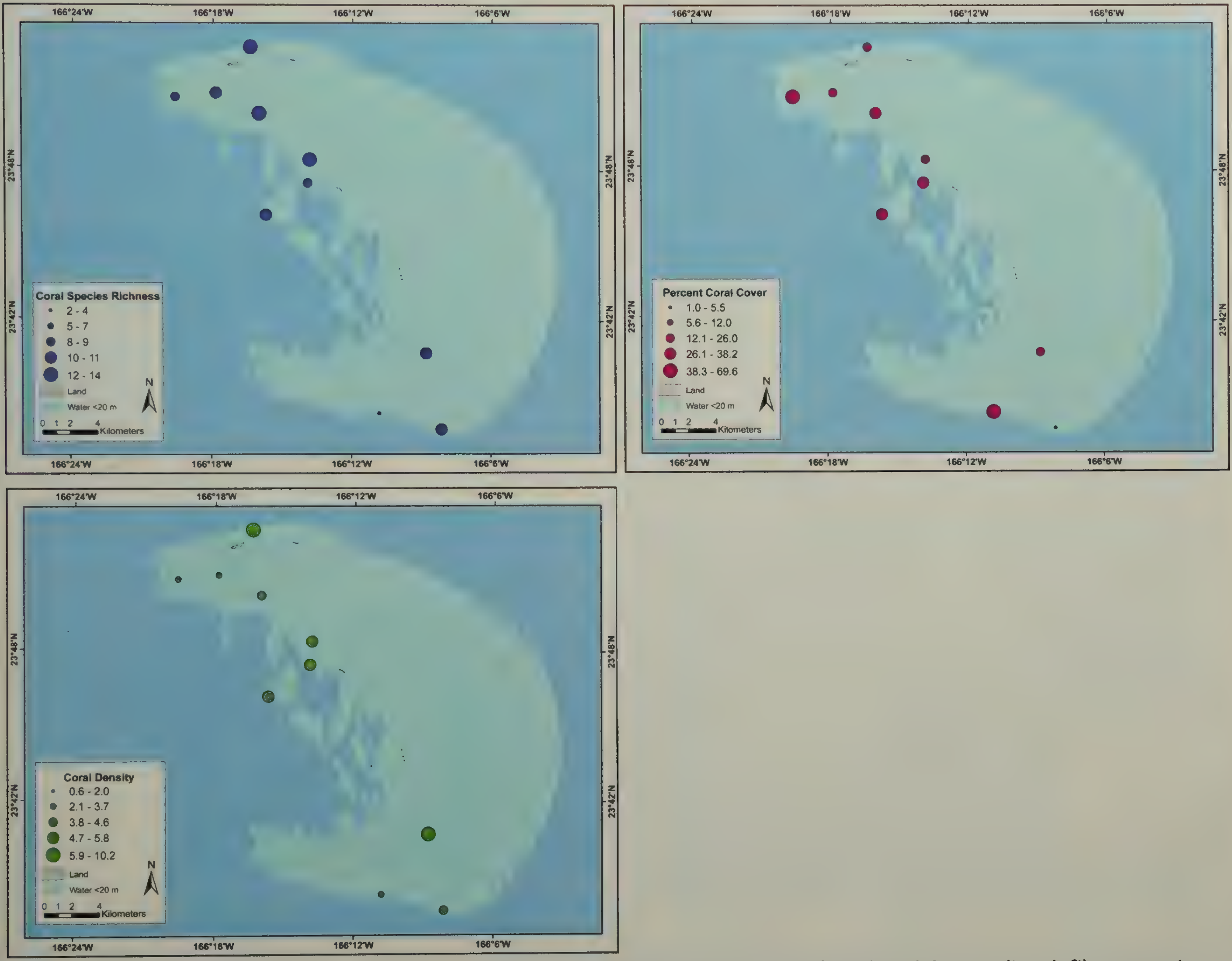


Figure 4.30. French Frigate Shoals coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Maro Reef

Species richness at Maro Reef was 9.1 per transect and ranked fourth overall (Table 4.10, Figure 4.31). Coral cover was high ($\bar{x}$ = 33.3, SD ± 17.8) and ranked second overall. Density was the second highest among all sites and averaged 5.43 colonies/m^{-2}.

Table 4.10. Descriptive statistics for corals from 2006 REA data at Maro Reef. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	9	9.11	1.45	0.48	7.99	10.23
Coral cover (%)	9	33.29	17.85	5.95	19.6	47.01
Density (no. m^{-2})	9	5.43	1.47	0.49	4.3	6.56

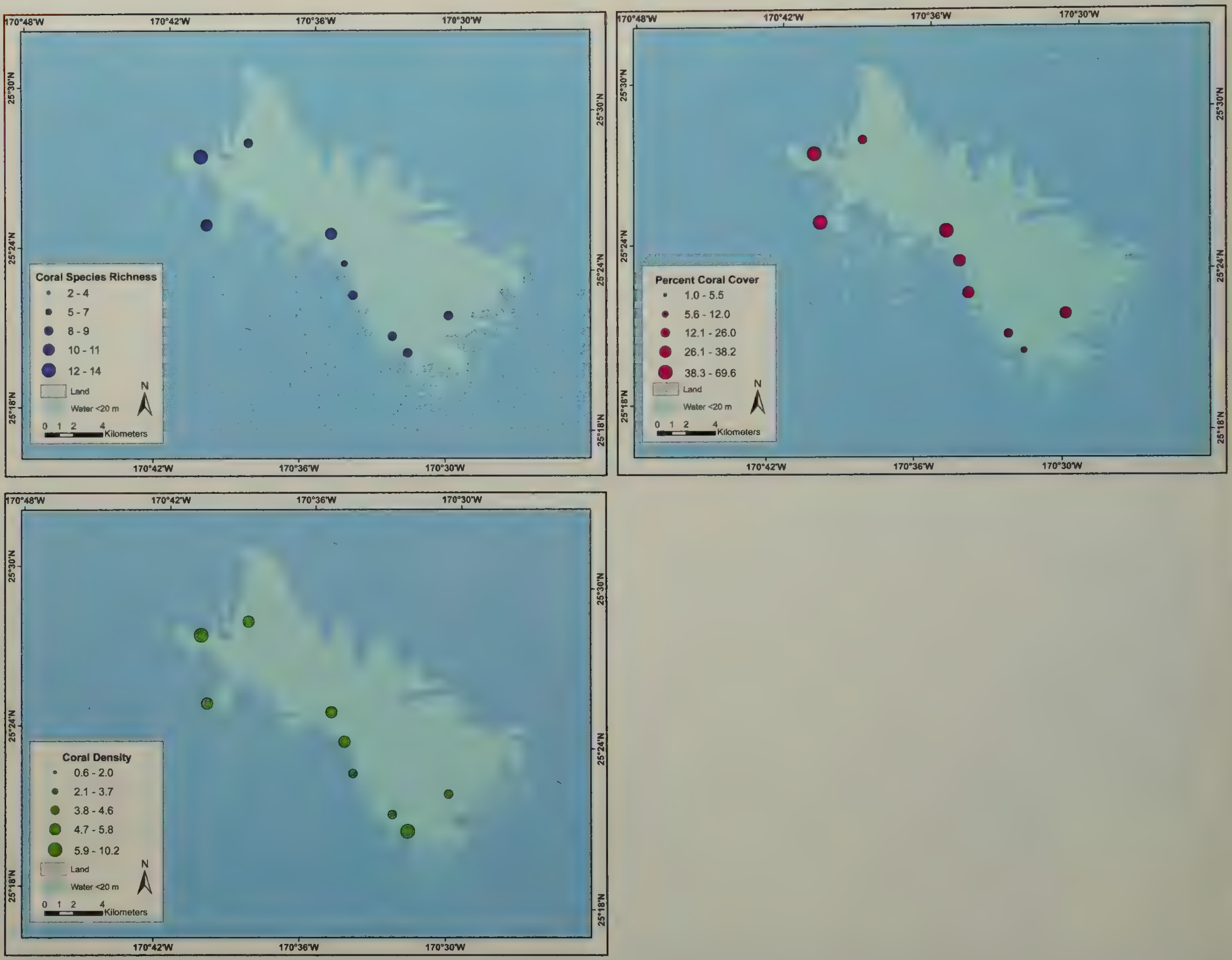


Figure 4.31. Maro reef coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Laysan Island

Lasyan Island had limited sampling effort in 2006 (Table 4.11; Figure 4.32). There were an average of 8.0 species recorded from transects, ranking fifth overall. Coral cover was also intermediate (fifth in rank) with an average cover of 17.7%. The density of coral colonies was low (seventh in overall rank) with an average of 2.8 coral colonies/m^{-2}.

Table 4.11. Descriptive statistics for corals from 2006 REA data at Laysan Island. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	3	8	1	0.58	5.52	10.48
Coral cover (%)	3	17.65	12.86	7.42	-14.3	49.59
Density (no. m^{-2})	3	2.84	1.06	0.61	0.2	5.48

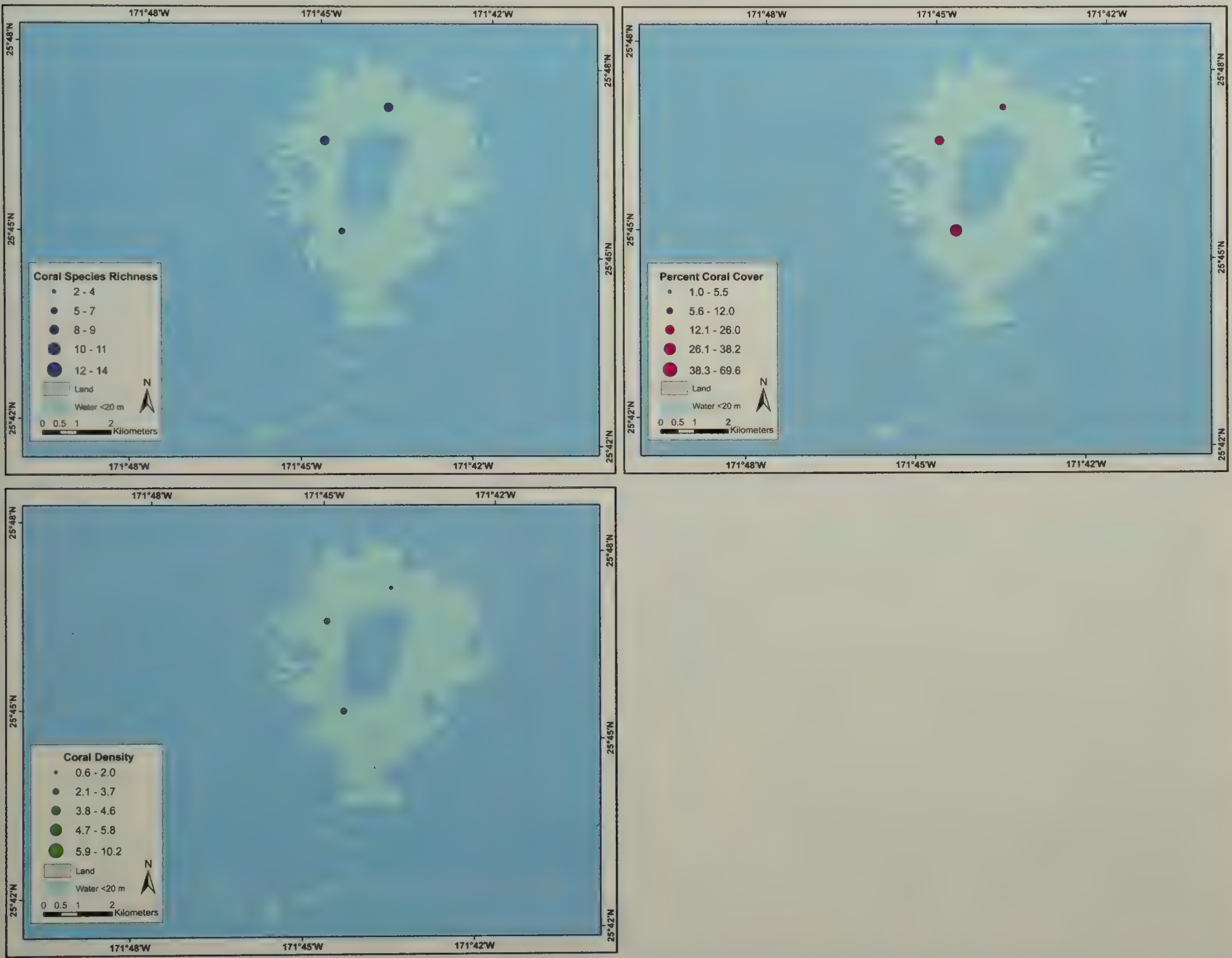


Figure 4.32. Laysan Island coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Lisianski-Neva Shoals

Lisianski-Neva Shoals averaged 10.8 coral species per transect and ranked second overall (Table 4.12, Figure 4.33). It ranked first in coral cover with an average of 36.7%. Density of coral colonies was intermediate with 4.3 colonies/m^{-2}.

Table 4.12. Descriptive statistics for corals from 2006 REA data at Lisianski. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	9	10.78	2.28	0.76	9.03	12.53
Coral cover (%)	9	36.74	20.77	6.93	20.8	52.71
Density (no. m^{-2})	9	4.27	1.54	0.51	3.08	5.45

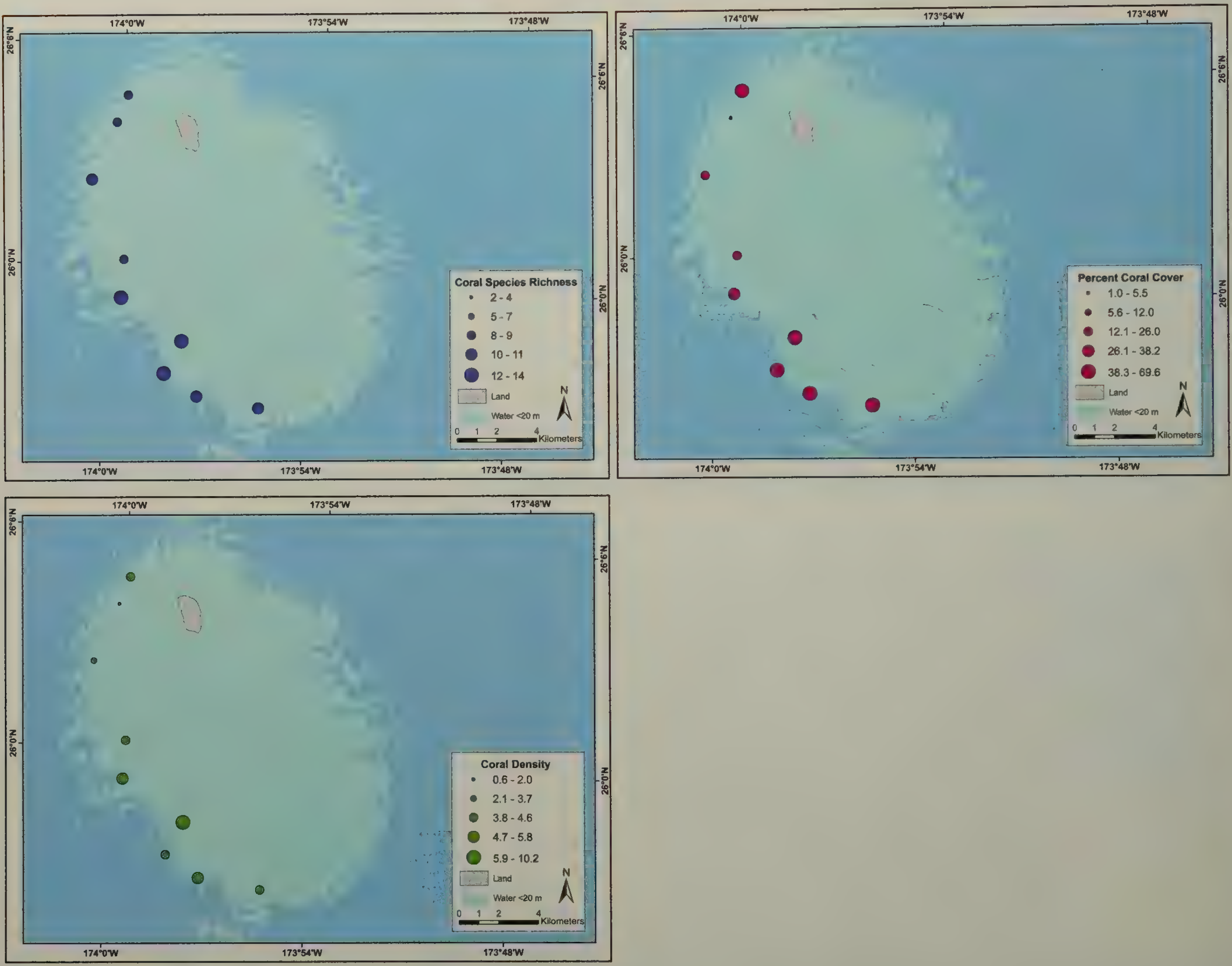


Figure 4.33. Lisianski-Neva Shoals coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Midway Atoll

Species richness of corals at Midway was the lowest of any reef surveyed in 2006 with an average of four species per transect (Table 4.13, Figure 4.34). Coral cover was 13.8% and ranked sixth overall. The density of coral colonies was 2.7/m^{-2}, which was also the lowest among all location.

Table 4.13. Descriptive statistics for corals from 2006 REA data at Midway Atoll. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	9	4.44	1.24	0.41	3.49	5.4
Coral cover (%)	9	13.81	17.74	5.91	0.17	27.44
Density (no. m^{-2})	9	2.68	1.98	0.66	1.15	4.2

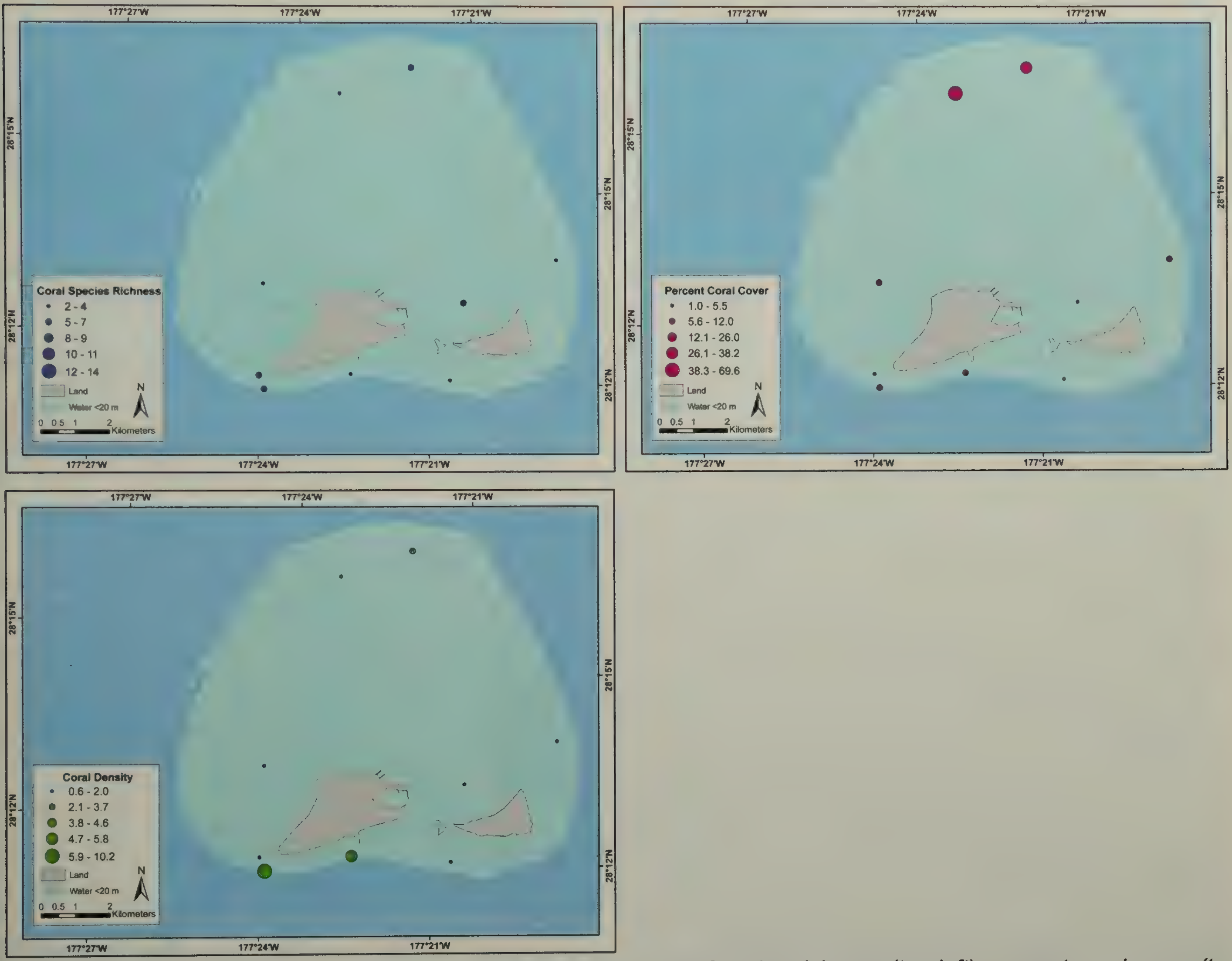


Figure 4.34. Midway Atoll coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Kure Atoll

Kure had the second lowest coral species richness with an average of six species per transect (Table 4.14, Figure 4.35). Coral cover was second lowest after Midway at 13.7%. Colony density was intermediate at 4.3 colonies/m^{-2} and ranked fourth overall.

Table 4.14. Descriptive statistics for corals from 2006 REA data at Kure Atoll. Source: NWHI RAMP, unpub. data.

CHARACTERISTIC	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Richness	9	6	2.24	0.75	4.28	7.72
Coral cover (%)	9	13.67	9.34	3.11	6.5	20.85
Density (no. m^{-2})	9	4.29	2.54	0.85	2.33	6.24

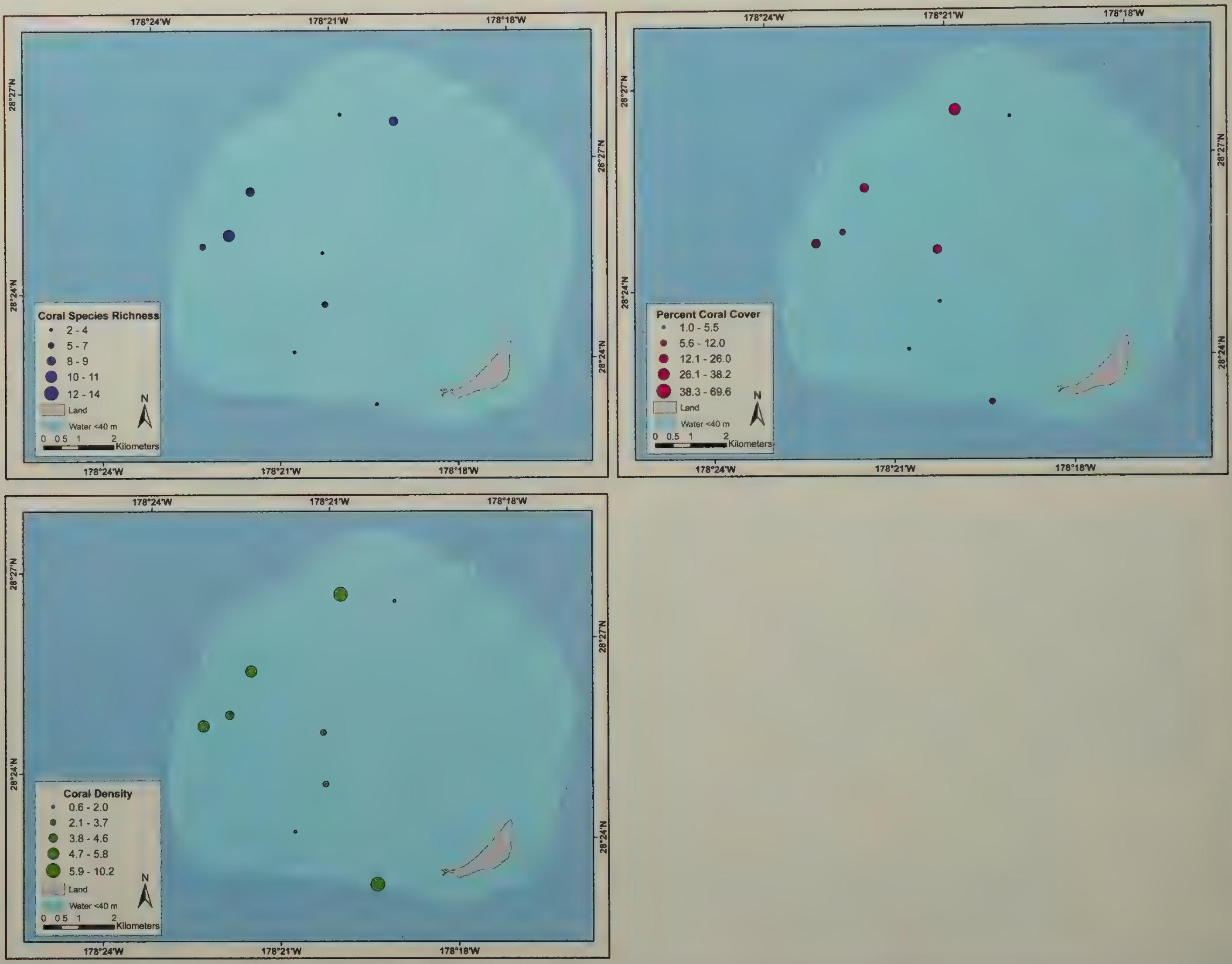


Figure 4.35. Kure Atoll coral statistics and distribution for 2006. Species richness (top left), percent coral cover (top right) and coral density (number m^{-2}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Changes In Coral Cover Over Time From Rapid Ecological Assessment Data

Most regions have low coral cover (<20%), with higher values at Maro, Lisianski and French Frigate Shoals. Coral cover values determined from REA surveys showed the highest coral cover values at Maro and Lisianski though their magnitude (>60%) was greater than the values derived from the line-intercept method in 2004-2006 (Figure 4.36). At each region, the coral cover values computed from the different survey years (2004, 2005 and 2006) are highly similar, indicating little change overall in each region.

Coral Settlement and Recruitment

In fall 2001 an array of recruitment plates was attached to the base of CREWS moorings at French Frigate Shoals, Maro, Lisianski, Pearl and Hermes, Midway and Kure to assess larval recruitment. The plates were collected in fall 2002 and fresh arrays were deployed which, in turn were collected in 2003. Coral recruits present on the plates were counted and measured with the use of a dissecting microscope. While the second cohort of plates were in the water for a shorter time period than the first cohort of recruitment plates that had been deployed between 2001 and 2002 (293 versus 376 days, respectively), the number of recruits was higher in 2003 (382) than in 2002 (Figure 4.37). Plates at Maro showed the highest number of recruits in both years. Nearly all juvenile recruits were from the family Pocilloporidae, though members of the families Acroporidae and Poritidae were also found on plates from French Frigate Shoals and Maro.

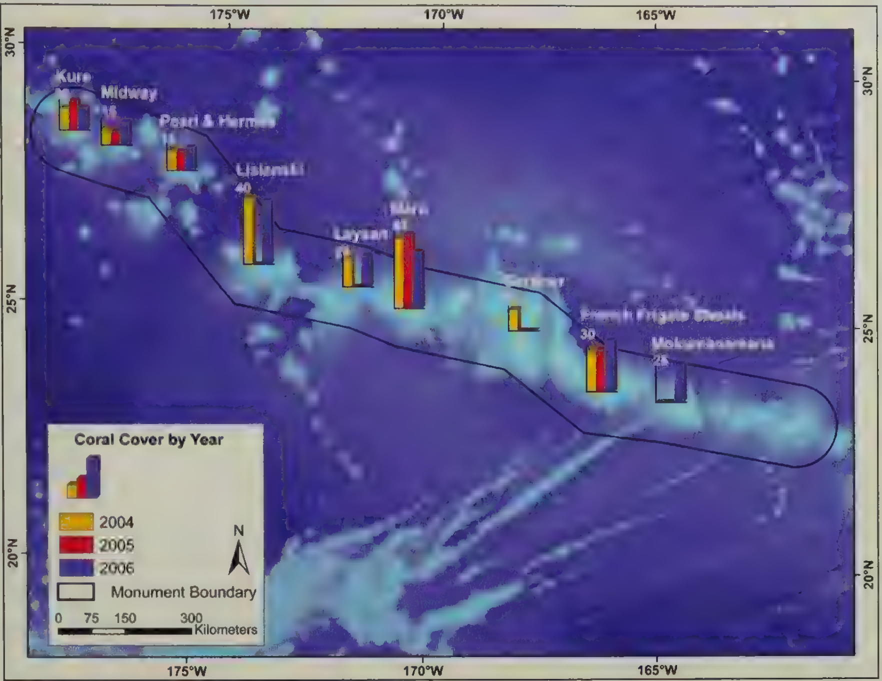


Figure 4.36. Differences in coral cover among regions within the NWHI. Not all regions were surveyed in all three years. Coral cover was calculated from the line-intercept method at 0.5 m intervals. Data are mean and standard error. Source: NWHI RAMP, unpublished data; map: L. Wedding.

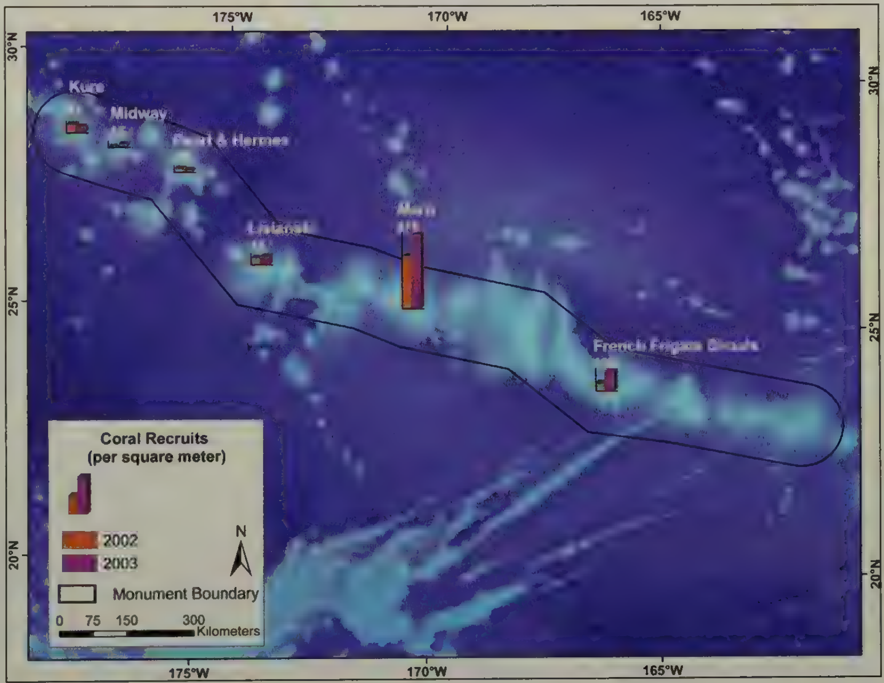


Figure 4.37. Density of coral recruits on plates deployed at six locations in the NWHI in 2002 and 2003. Source: NWHI RAMP; map: L. Wedding.

Coral Bleaching

Mass coral bleaching affected numerous shallow reefs through the NWHI in 2002 and 2004 (Figure 4.38). In both years, the incidence of bleaching was greater at the three northern atolls (Pearl and Hermes, Midway and Kure) than at Lisianski and farther south. At the three northern atolls, bleaching was most severe in shallow back reef and lagoon habitats. In both years, colonies in the genus *Montipora* and *Pocillopora* sustained the highest levels of bleaching (Kenyon et al., 2006; Kenyon and Brainard, 2006). In comparison, only low levels of bleaching were observed during 2006 surveys (Figure 4.38), which were conducted at the same time of year (September) as those in 2002 and 2004. Colonies in the genus *Montipora* were again most affected by bleaching in 2006.

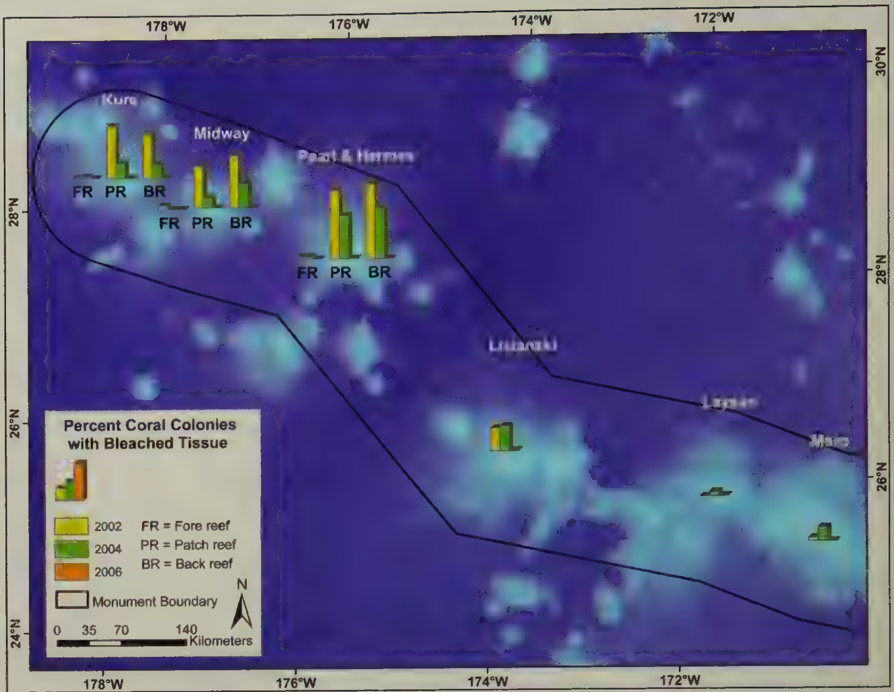


Figure 4.38. Percentage of colonies with bleached tissue within belt transects surveyed in 2002, 2004 and 2006. Minimal bleaching was seen at Gardner Pinnacles and French Frigate Shoals, which are not shown to reduce the complexity of the figure. Source: NWHI RAMP; map: L. Wedding.

In 2004, visual estimates of mortality and algal overgrowth of *Montipora capitata* and *M. cf. turgescens* at back reef sites at the three northern atolls conservatively exceeded 50%, with nearly complete mortality of surface-facing portions of colonies at numerous sites. The shallow crest of a large central patch reef system at Kure Atoll, previously referred to as "the coral gardens" due to its luxuriant growth of montiporids and pocilloporids, was heavily bleached in 2002. In 2004, only a few branches of *Porites compressa* remained alive and the dead coral skeletons were thickly covered in turf and macroalgae. Little change was seen in this reef's condition in 2006. A striking shift occurred at this location from a system dominated by coral in 2001 to a system dominated by algae in 2004 (Figure 4.39).

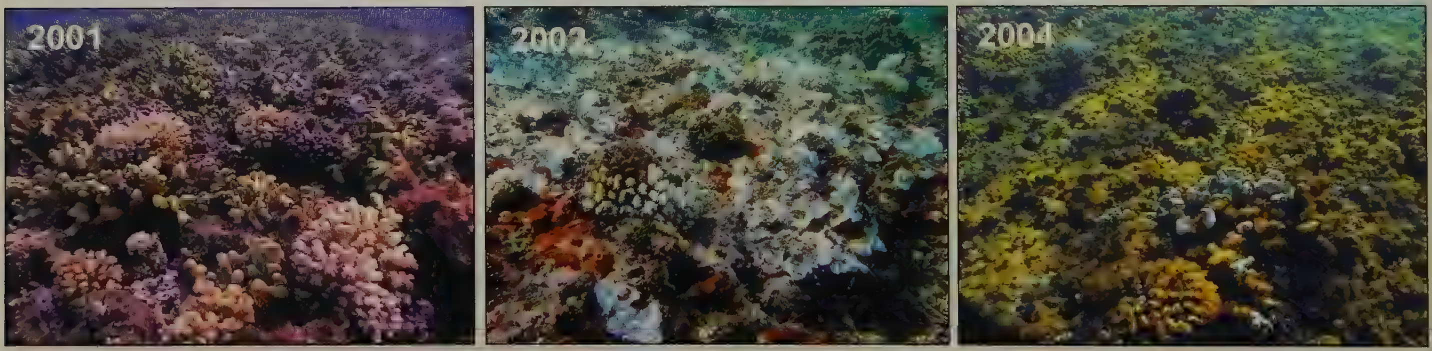


Figure 4.39. Phase shift on a patch reef at Kure Atoll from a benthos dominated by coral to one dominated by algae after a bleaching event in 2002. Photos: J. Kenyon.

Distribution of Coral Disease

Coral disease has emerged as a serious threat to coral reefs worldwide and a major cause of reef deterioration (Weil et al., 2006). The numbers of diseases and coral species affected, as well as the distribution of diseases, have all increased dramatically within the last decade (Porter et al., 2001; Green and Bruckner, 2000; Sutherland et al., 2004; Weil, 2004). Changing climatic conditions as well as local anthropogenic stressors have been implicated in increased disease levels but our ability to fully understand recent disease outbreaks is hampered by the paucity of baseline and epidemiological information on the normal disease levels in the ocean (Harvell et al., 1999, 2002). The NWHI is considered to be one of the last relatively pristine large coral reef ecosystems remaining in the world. As such, it provides the unique opportunity to document the normal levels of disease in a coral reef system exposed to limited human influence and the potential of understanding disease dynamics in response to changing climatic conditions.

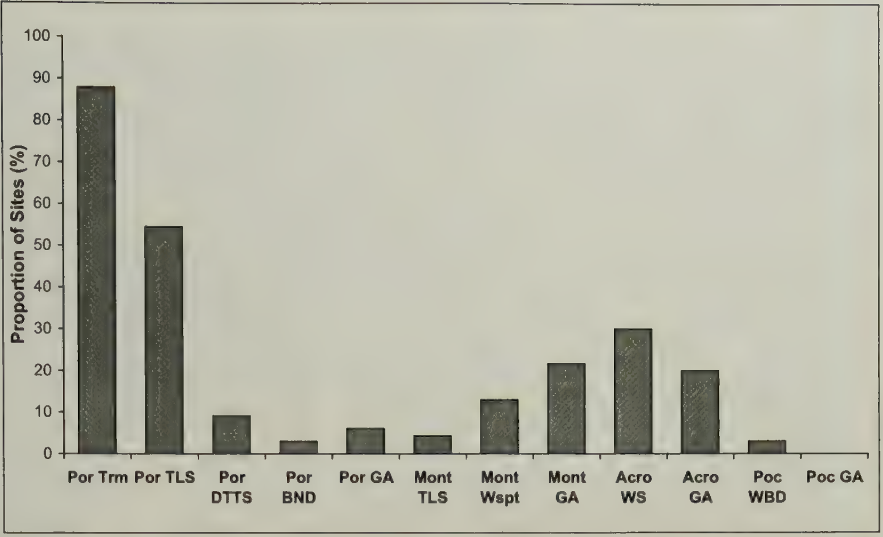


Figure 4.40. Frequency of occurrence of different coral diseases within the NWHI. Data based on 33 REA surveys conducted in 2005. Source: NWHI RAMP, unpub. data.

Table 4.15. Distribution on of twelve coral diseases based on REA surveys conducted between 2002-2005. Source: Aeby, unpub. data.

	MMM	FFS	GAR	MAR	LAY	LIS	PHR	MID	KUR
Por TRM	X	X	X	X	X	X	X	X	X
Por TLS		X		X	X	X	X	X	X
Por DTTS		X		X	X	X	X	X	X
Por BND						X	X		
Por GA				X			X		X
Mont WS				X	X	X	X	X	X
Mont MFTL				X				X	X
Mont GA		X		X	X		X		
Acroporid WS		X							
Acro GA		X							
Poc WB							X		X
Poc GA	X								
Total # Diseases	**2**	**6**	**1**	**7**	**5**	**5**	**8**	**5**	**7**

Coral disease abbreviations: Por = *Porites,* Mont = *Montipora,* Acro =*Acropora,* Poc = *Pocillopora,* TRM = trematodiasis, WS = white syndrome, WB = white band,TS = tissue loss syndrome, DTTS = discolored tissue thinning syndrome, BND = brown necrotising disease, GA = growth anomaly, MFTL = multifocal tissue loss

During a multi-agency cruise conducted in September 2002, disease investigation was incorporated into the protocol and a characterization of coral diseases was initiated. In 2003, baseline coral disease surveys were conducted at 73 permanent monitoring sites throughout the NWHI and have since been surveyed annually. Twelve disease states have now been documented in the four major genera of coral (*Porites, Montipora, Pocillopora and Acropora*) on the reefs of the NWHI (Figure 4.40). The distribution and frequency of occurrence of the different coral diseases varied widely within the nine islands/atolls of the NWHI (Table 4.15; Figure 4.41). The most common disease is *Porites* trematodiasis (Figure 4.42) caused by the digenetic trematode, *Podocotyloides stenometra* (Aeby, 1998*)*. This disease is widespread (69.8% of the sites in 2003) and is known to exclusively affect *Porites* sp. coral (Aeby, 2006). Other diseases are less common, such as *Porites* brown necrotizing disease, which only occurred at only 3.2% of the sites in 2003 (Aeby, 2006). Patterns in disease prevalence among the coral genera suggest *Acropora* is highly susceptible to disease and *Pocillopora* appears to be very resistant. *Acropora* comprised only 2.2% of the overall coral community along transects, yet showed high overall prevalence of disease (Aeby, 2006). In contrast, pocilloporids are a common coral in the NWHI (21.1% of the overall coral community along transects) yet seldom showed signs of disease (Aeby, 2006). In contrast, Willis et al. (2004) found pocilloporids on the Great Barrier Reef to have the highest prevalence of disease among all coral families surveyed despite pocilloporids having the lowest coral cover.

Although coral disease was found to be widespread on the reefs of the NWHI, disease prevalence (proportion of colonies affected) for most coral diseases, with the exception of *Porites* trematodiasis, was found to be low in a healthy ecosystem (2005: average prevalence = 0.43% SE ± 0.1%; n = 37 sites surveyed; Figure 4.43). In contrast, the average prevalence of *Porites* trematodiasis in 2005 was 12.5% (SE ± 3.2%; n=36 sites surveyed). *Porites* trematodiasis is an unusual coral disease, in that, it is caused by a larval trematode, which is transmitted through the food chain and requires multiple hosts (coral, mollusk, fish) for completion of its life cycle (Aeby, 1998). In contrast, most coral diseases are caused by bacteria or viruses that can be transmitted directly (host to host) or through the water column. For *Porites* trematodiasis, prevalence of the disease is dependent upon and thus reflective of the abundance of its three hosts. Hence it is not surprising to find high prevalence of this disease on the pristine reefs of the NWHI where host abundance is high. Similarly, Aeby (2007) examined the prevalence of *Porites* trematodiasis in Kaneohe Bay, Oahu which has a distinct north-south gradient in rural to urbanized watersheds. Most of the human population in surrounding watersheds is concentrated in the southern sector and so the south Bay has been most affected by impacts of urbanization (Maragos et al., 1985; Hunter and Evans, 1995). Aeby (unpub. data) found disease levels to be higher in the north Bay than in the south Bay and concluded that host abundance, not environmental stressors, was the primary factor affecting prevalence of *Porites* trematodiasis in Kaneohe Bay. Prevalence of disease varied among islands (Figure 4.44) and differed among coral genera at each island. In 2005, Maro had the highest prevalence of montiporid disease whereas Kure had the highest level of poritid disease. It is not yet clear why differences in disease prevalence occur among islands. Understanding patterns of disease occurrence will require much more information on disease epizootiology such as etiology and mode of transmission.

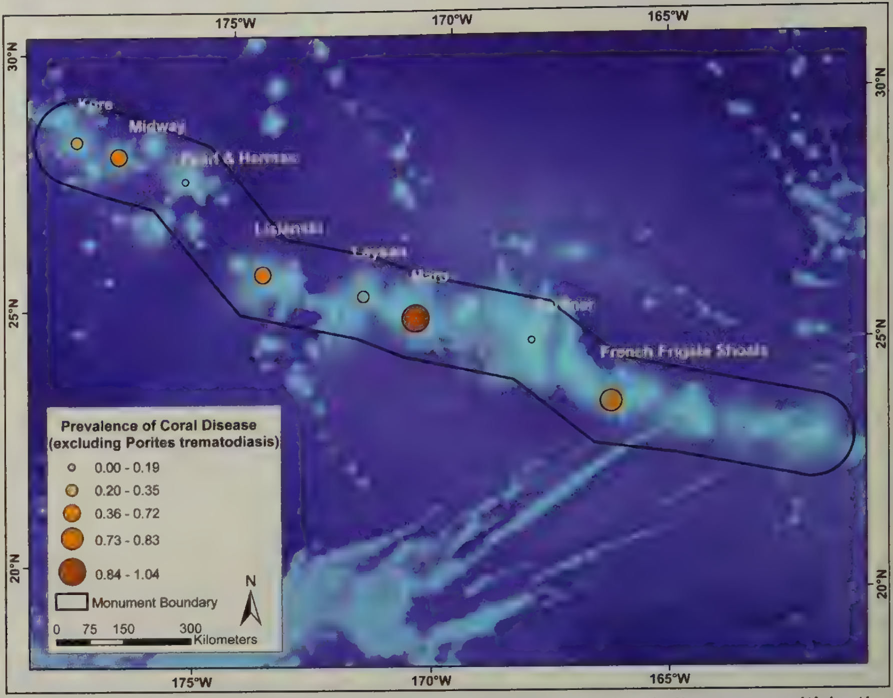


Figure 4.41. Frequency of occurrence of different coral diseases within the NWHI. Data based on 33 REA surveys conducted in 2005. Source: Aeby; unpub. data; map: L. Wedding.

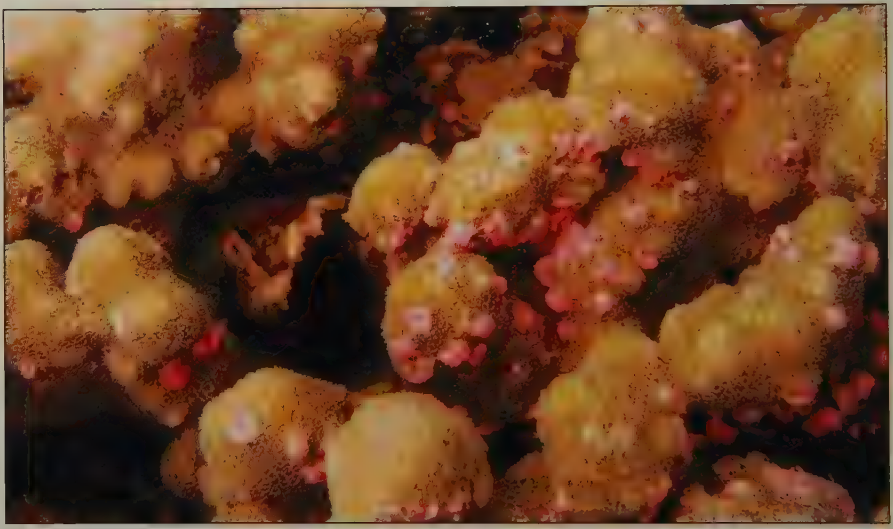


Figure 4.42. Porites trematodiasis *is caused by a larval trematode, which is transmitted through the food chain and requires multiple hosts (coral, mollusk, fish) for completion of its lifecycle. Photo: G. Aeby.*

Prevalence of the disease is dependent upon and thus reflective of the abundance of its three hosts. Hence it is not surprising to find high prevalence of this disease on the pristine reefs of the NWHI where host abundance would also be high. One exception to the pattern of healthy levels of coral disease on the reefs of the NWHI is an outbreak of *Acropora* white syndrome (AWS) that was first documented at French Frigate Shoals in 2003 (Aeby, 2006b). AWS has caused significant coral loss on reefs at French Frigate Shoals (Aeby, unpub. data), as well as in other areas of the Indo-Pacific (Willis et al., 2004; Jacobson, 2006). As of 2006, studies found the disease to have spread to seven reefs within French Frigate Shoals. Acroporids have also been greatly affected by disease in Australia (Willis et al., 2004) and the Marshall Islands (Jacobson, 2006) and have been decimated by disease in the Caribbean (Green and Bruckner, 2000; Porter et al., 2001; Patterson et al., 2004; Weil, 2004). Acroporids were one of the major frame-building corals in the Florida Keys, but losses of acroporids are now averaging 87% or greater (Miller et al., 2002; Patterson et al., 2002). Research is desperately needed to understand disease processes to prevent the acroporid reefs of the Monument and neighboring Johnston Atoll National Wildlife Refuge from following the same path as the acroporid reefs of the Florida Keys. More research is also needed to understand disease transmission dynamics across Indo-Pacific and the impact climate change will have on the health of coral reef ecosystems.

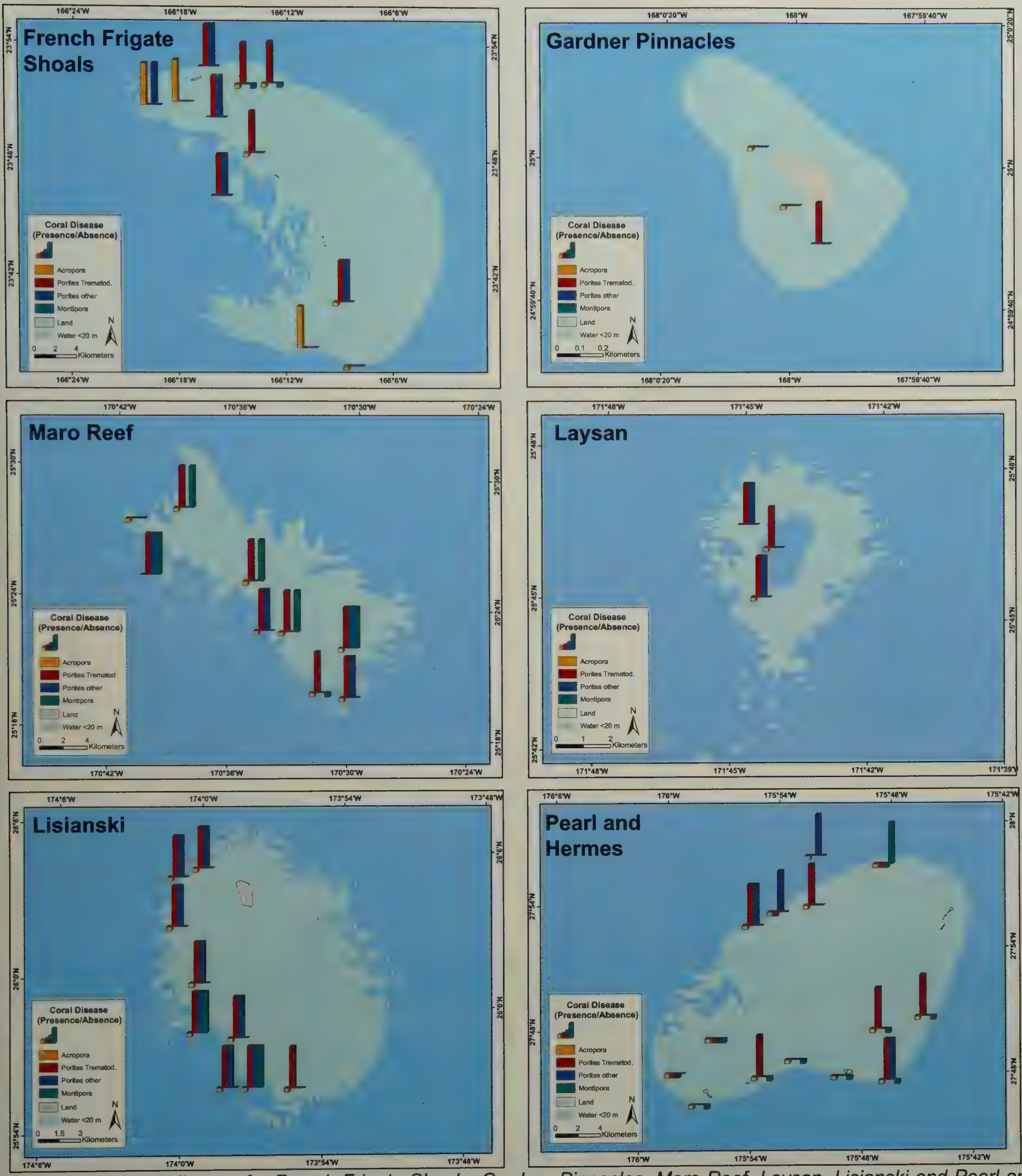


Figure 4.43. Coral disease for French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan, Lisianski and Pearl and Hermes. Source: Aeby, unpub. data; maps: L. Wedding.

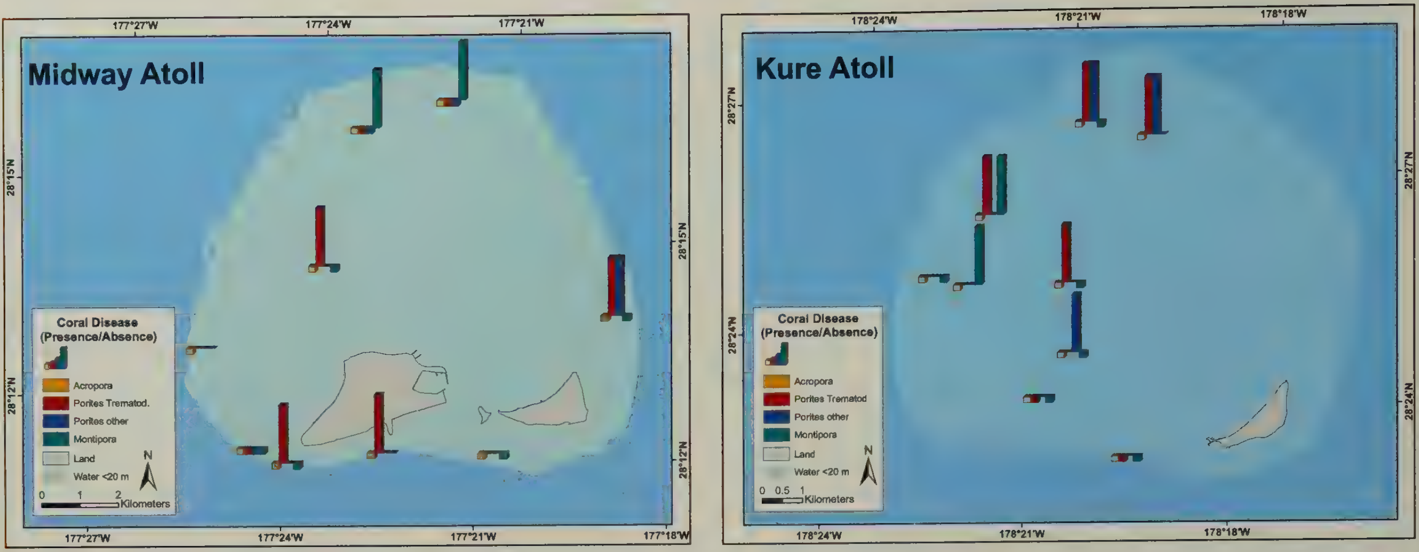


Figure 4.43 (continued). Coral disease at Midway and Kure atolls. Source: Aeby, unpub. data; maps: L. Wedding.

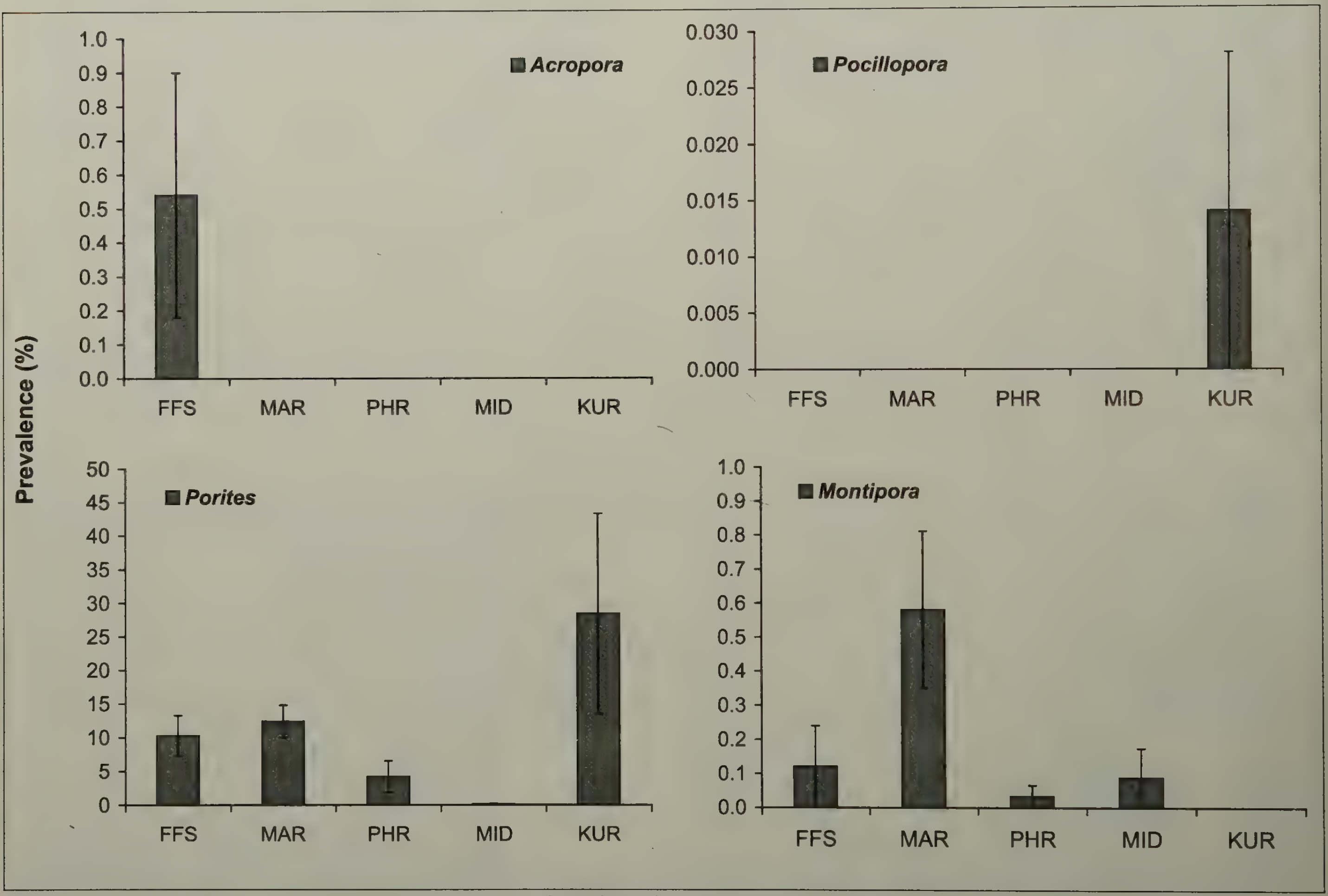


Figure 4.44. Prevalence of coral disease among locations by major coral genera. Note the differences in y-axis among genera. Source: G. Aeby, unpub. data.

Coral Predators

The Crown-of-thorns starfish (COTS; *Acanthaster planci*; Figure 4.45) and Drupellid snails (*Drupella* sp.) are both corallivores that have caused significant coral damage in other areas of the Indo-Pacific, and were monitored on the reefs of the NWHI during benthic and towed-diver surveys. Towed-diver surveys report COTS to be present on the reefs of the NWHI but to occur at low levels (average=0.65 COTS/km; NWHI Reef Assessment and Monitoring Program or RAMP, unpub. data). During annual benthic monitoring surveys it was found that the frequency of occurrence (the number of sites with animals or feeding scars/total sites surveyed) for *Drupella* sp. was low (3% in 2004, 15.4% in 2005) (Aeby, unpub. data). *Drupella* were usually found feeding at the base of branches of cauliflower coral (*Pocillopora meandrina*). For COTS, frequency of occurrence was also low with reports of COTS observed at 4.5% of the monitoring sites in 2004 and 28.2% in 2005 (Aeby, unpub. data). COTS were usually found as single animals.

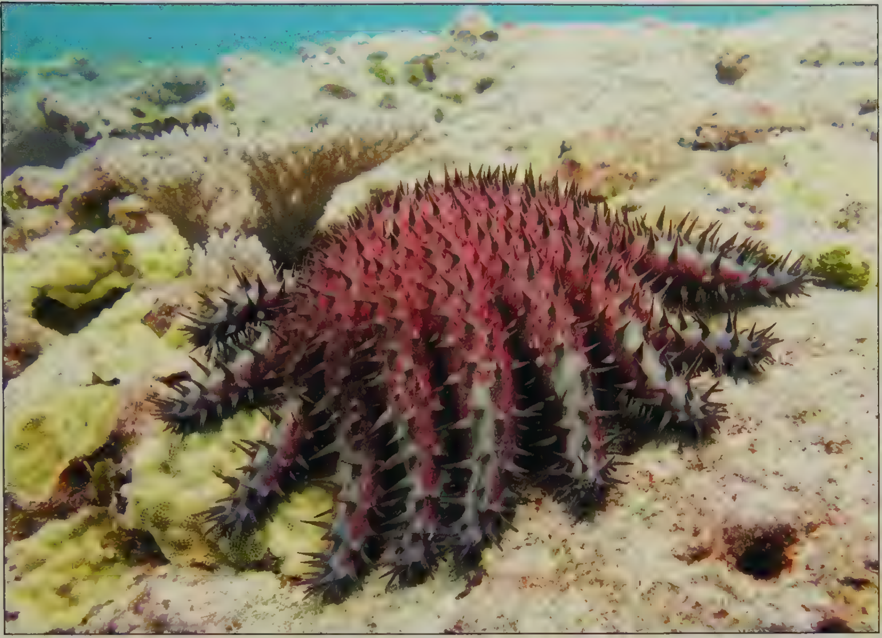


Figure 4.45. Crown-of-thorns sea star in the NWHI. Photo: J. Kenyon.

ALGAE

Although the NWHI represent one of the last relatively intact tropical reef ecosystems in the world, macroalgal community dynamics of the 10 atolls, islands, and reefs situated in the NWHI Marine National Monument remain poorly understood. A study published in conjunction with the Northwestern Hawaiian Islands' third Scientific Symposium (Vroom and Page, 2006) was the first to provide distributional maps of common algal species, statistically compare sites from differing habitats and islands based on relative abundance of macroalgae and look for temporal differences in macroalgal populations. Findings revealed that the abundance of most macroalgal genera was low across the archipelago, but that members of certain green algal genera including *Halimeda* and *Microdictyon* (Figure 4.46) can be extremely common and in some cases form dense monotypic meadows on the reef, especially in fore reef areas (*Microdictyon*) and lagoons (*Halimeda*). Other genera, such as the brown algae *Stypopodium* and *Lobophora*, and the red alga *Laurencia*, become increasingly prevalent in the three northwestern-most atolls of the Hawaiian archipelago (Kure, Midway, and Pearl and Hermes). Relative abundance of macroalgae across the NWHI chain as a whole remained relatively static for the years surveyed; however, slight changes occurred at Kure and Midway atolls where coral bleaching events were documented in 2002 and 2004.

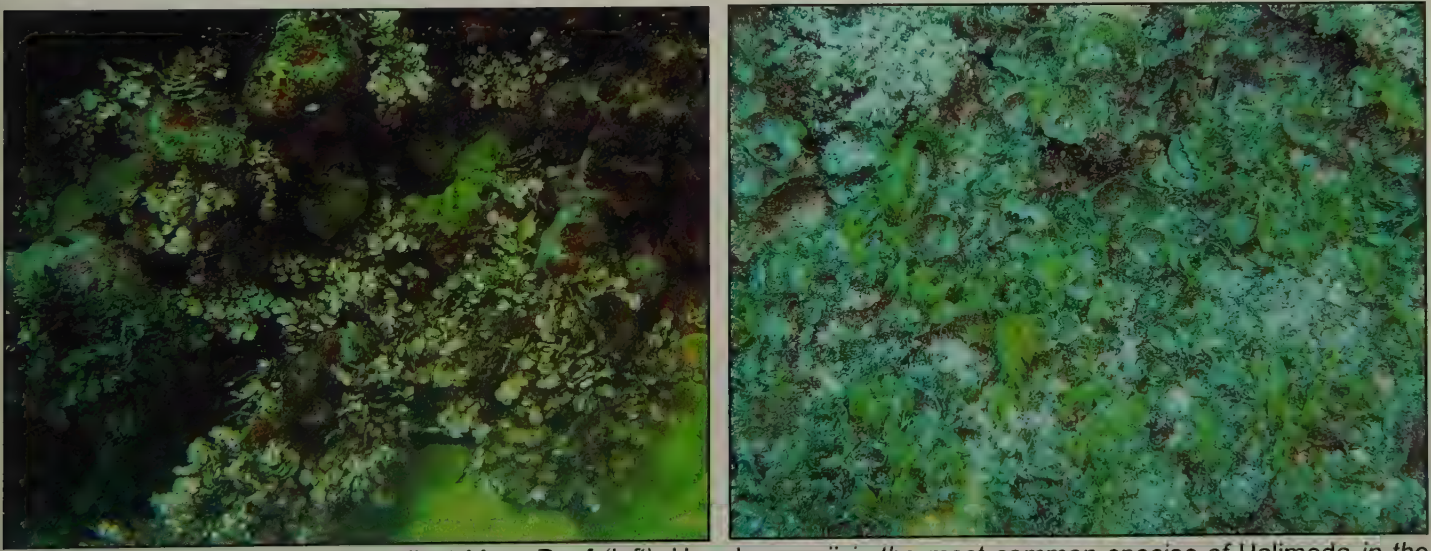


Figure 4.46. Halimeda velasquezii *at Maro Reef (left).* H. velasquezii *is the most common species of* Halimeda *in the NWHI.* Microdictyon *is also very common in some regions of the NWHI. A close-up photo of a* Microdictyon setchellianum *(right) field at Gardner Pinnacles. Photos: P. Vroom.*

A study recently completed at Pearl and Hermes Atoll (Page, 2006) used detailed species-level percent cover analyses coupled with environmental variables to better understand the mechanisms that determine distributional patterns of organisms, particularly algae. Benthic community composition was examined along a wave exposure gradient using multivariate statistical analyses with the hypothesis that sites with similar levels of wave exposure would exhibit similar benthic communities. Species richness of coral and macroalgae were also compared to determine if sites with intermediate levels of wave exposure would contain the highest diversity of benthic organisms. To test these hypotheses, percent cover of benthic organisms was determined at 34 sites in four wave exposure categories: high, intermediate-high, intermediate-low and low. Multivariate statistical analyses revealed that sites from each wave exposure category differed significantly, and a non-metric multi-dimensional scaling ordination (nMDS) and cluster diagram grouped sites from low, high, and intermediate-high wave disturbance areas into three relatively discrete clusters. However, sites experiencing intermediate-low wave exposure did not group together in the nMDS ordination or cluster diagram, suggesting variability in benthic compositions among these sites. Coral and macroalgal species richness was significantly higher at sites with intermediate-high and intermediate-low levels of wave exposure than at sites with low wave exposure, although not significantly higher than sites with high wave exposure.

An article appearing in *American Scientist* magazine (Vroom et al., 2006) compared percent cover of macroalgal, turf algal, crustose coralline algal and coral populations at eight islands across the Pacific Ocean basin, including two from the NWHI. The NWHI are documented to contain the highest percent cover of algal species when compared to other geographic locations, and the lowest percent cover of living coral. This is likely due to the subtropical location of the NWHI and cool SSTs that bathe biological communities during winter months. Despite high algal populations, the NWHI remain healthy and thriving marine ecosystems that are dominated by top predators and high fish populations.

Algal diversity appears similar across the NWHI chain even though brown algae tend to be more abundant at Midway and Kure atolls when compared to most other islands (Figure 4.47). The lower abundance of green algae at Midway may be tied to lower apex predator biomass and higher herbivorous fish densities at this atoll system, suggesting possible top-down control of the benthic habitat (DeMartini and Friedlander, 2004, 2006).

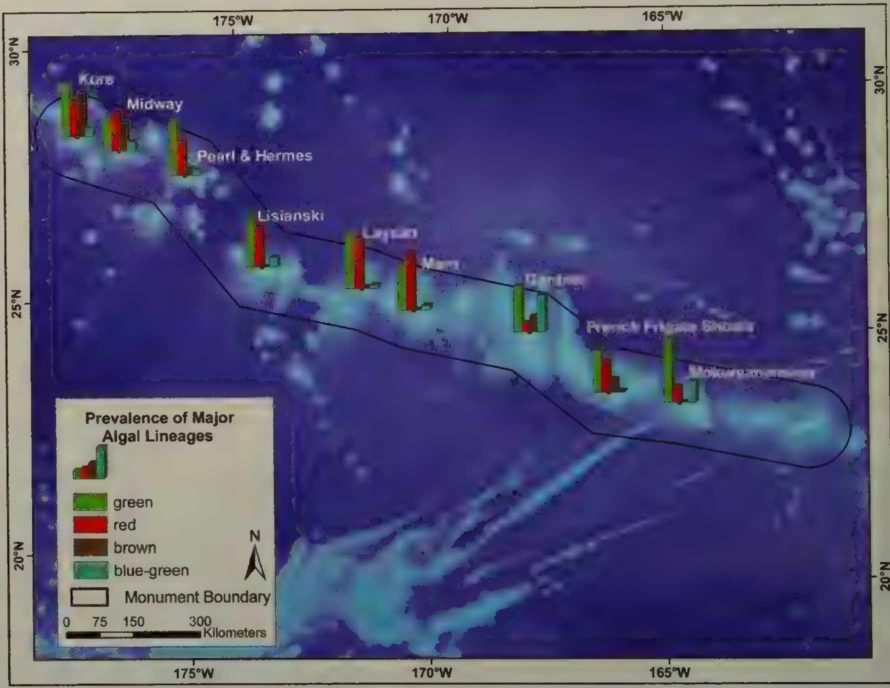


Figure 4.47. Prevalence of major algal lineages in the Northwestern Hawaiian Islands. Bars represent standard deviation. Source: NWHI RAMP, unpub. data; map: L. Wedding.

Although the mix of macroalgal species is relatively similar throughout the NWHI chain, certain species (e.g., *Stypopodium flabelliforme*, *Laurencia galtsoffii*) are more abundant in the northwesternmost atolls where SSTs experience the greatest annual fluctuation. While *S. flabelliforme* is a major component of shallow reef systems at Kure Atoll, it is a minor component of reefs at most other islands and atolls in the NWHI. Because brown algae are known to predominate over other algal lineages in cool, temperate environments (Cheney, 1977), it is possible that the cooler SSTs found at Kure and Midway atolls during winter months may favor a higher abundance of brown algal species (Figure 4.47).

Algae Data: 2006

Mokumanamana

Only two stations were assessed for algae at Mokumanamana in 2006 (Figure 4.48; located on pages 144-145). It is a composite of maps illustrating the percent frequency of occurrence of major algae by island). Four algal groups were present with *Halimeda* occurring in 100% of the samples, followed by *Laurencia* (91.7%), crustose coralline red algae (12.5%) and *Jania* (8.3%; Table 4.16).

Table 4.16. Summary statistics for algal groups at Mokumanamana Island in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	0	0	0	0.00%
Halimeda	100	0	2	100.00%
Microdictyon	0	0	0	0.00%
Neomeris	0	0	0	0.00%
Jania	8.33	11.79	1	50.00%
Laurencia	91.67	11.79	2	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	12.5	17.68	1	50.00%
Lobophora	0	0	0	0.00%
Padina	0	0	0	0.00%

French Frigate Shoals

Ten stations were sampled in 2006 at French Frigate Shoals with seven algal groups present on quantitative surveys (Table 4.17, Figure 4.48). *Laurencia* was present all stations and found, on average, in 77% of quadrats. *Halimeda* was present at 90% of the stations and found, on average, in 62% of the quadrats. *Jania* was found at half the stations but on occurred in 9% of the quadrats, on average.

Table 4.17. Summary statistics for algal groups at French Frigate Shoals in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	1.67	5.27	1	10.00%
Halimeda	62.5	38.14	9	90.00%
Microdictyon	15.83	21.68	4	40.00%
Neomeris	0	0	0	0.00%
Jania	9.17	15.44	5	50.00%
Laurencia	76.67	20.71	10	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	0	0	0	0.00%
Lobophora	30	32.68	8	80.00%
Padina	2.5	7.91	1	10.00%

Maro Reef

Nine stations were sampled at Maro Reef in 2006 with six algal groups present (Table 4.18, Figure 4.48). *Halimeda* was present at all stations and found, on average, in 91% on the quadrats. *Laurencia* was also found at all stations and occurred in 75% of the quadrats. Crustose coralline red algae were found at three-quarters of the stations surveyed and appeared an average of 34% of the quadrats.

Table 4.18. Summary statistics for algal groups at Maro Reef in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	5.56	8.33	4	44.44%
Halimeda	90.74	6.51	9	100.00%
Microdictyon	0	0	0	0.00%
Neomeris	0	0	0	0.00%
Jania	12.96	19.59	4	44.44%
Laurencia	75	19.09	9	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	34.26	36.43	6	66.67%
Lobophora	27.78	30.33	6	66.67%
Padina	0	0	0	0.00%

Laysan Island

Three stations were surveyed at Lasyan Island in 2006 with eight algal groups observed in these surveys (Table 4.19, Figure 4.48). *Halimeda* and *Laurencia* were found at all stations and were the dominant groups being found, on average, in 89% and 86% of all quadrats, respectively. Crustose coralline red algae occurred at two of the three stations and were present in 44% of the quadrats, on average.

Table 4.19. Summary statistics for algal groups at Laysan Island in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	0	0	0	0.00%
Halimeda	88.89	19.25	3	100.00%
Microdictyon	19.44	33.68	1	33.33%
Neomeris	2.78	4.81	1	33.33%
Jania	8.33	14.43	1	33.33%
Laurencia	86.11	17.35	3	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	44.44	38.49	2	66.67%
Lobophora	19.44	4.81	3	100.00%
Padina	5.56	9.62	1	33.33%

Lisianski-Neva Shoals

Eight stations were sampled at Lisianski-Neva Shoals in 2006 with eight algal groups present in those surveys (Table 4.20, Figure 4.48). *Halimeda* occurred at all stations and in nearly all quadrats (94%). Other important genera included *Laurenica*, which was present in 78% of the quadrats, and *Jania*, which occurred in 42% of the quadrats. Both genera were present at 89% of the stations surveyed.

Table 4.20. Summary statistics for algal groups at Lisianski-Neva Shoals in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	12.96	13.89	6	66.67%
Halimeda	93.52	8.1	9	100.00%
Microdictyon	25	33.59	5	55.56%
Neomeris	10.19	11.62	5	55.56%
Jania	42.59	33.19	8	88.89%
Laurencia	77.78	31.18	8	88.89%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	1.85	5.56	1	11.11%
Lobophora	25	16.14	8	88.89%

Pearl and Hermes Atoll

A total of 12 stations were sampled at Pearl and Hermes in 2006 with nine algal groups present in those surveys (Table 4.21; Figure 4.48). *Laurencia* occurred at the greatest number of stations (92%), followed by *Halimeda* (75%), *Microdictyon* (67%), *Dictyosphaeria* (67%) and *Lobophora* (58%). On average *Halimeda* was present in 49% of quadrats, followed by *Microdictyon* with 42%, and *Laurencia* with 40%. Although *Dictyosphaeria* had a high frequency of occurrence, it was only present in 12% of the quadrats, on average.

Table 4.21. Summary statistics for algal groups at Pearl and Hermes Atoll in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	MEAN	SD	FREQ	% FREQ
Dictyosphaeria	11.81	12.54	8	66.67%
Halimeda	49.31	39.64	9	75.00%
Microdictyon	41.67	44.1	8	66.67%
Neomeris	4.86	10.33	3	25.00%
Jania	20.14	23.15	6	50.00%
Laurencia	40.28	31.15	11	91.67%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	18.75	32.4	4	33.33%
Lobophora	29.86	36.66	7	58.33%
Padina	10.42	26.38	3	25.00%

Midway Atoll

Sampling at Midway Atoll in 2006 included six stations with eight algal groups present (Table 4.22, Figure 4.48). Laurencia was found at all stations and 39% of the quadrats. *Lobophora* was found at 83% of the stations and occurred in 47% of the quadrats, on average. Microdicyton was found at half the stations and occurred in 22% of the quadrats. Padina was present at two-thirds of the stations (19% of the quadrats).

Table 4.22. Summary statistics for algal groups at Midway Atoll in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	**MEAN**	**SD**	**FREQ**	**% FREQ**
Dictyosphaeria	6.94	13.35	2	33.33%
Halimeda	11.11	16.39	3	50.00%
Microdictyon	22.22	32.77	3	50.00%
Neomeris	0	0	0	0.00%
Jania	1.39	3.4	1	16.67%
Laurencia	38.89	19.48	6	100.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	12.5	16.46	3	50.00%
Lobophora	47.22	24.53	5	83.33%
Padina	19.44	21.52	4	66.67%

Kure Atoll

Eight stations were sampled at Kure Atoll in 2006 with eight algal groups present (Table 4.23, Figure 4.48). *Microdictyon* was the most abundant genera, occurring at all stations and in 62% of all quadrats. *Halimeda* also was present at all stations but in a lower percentage of quadrats (25%). *Jania* and *Lobophora* were both present at 87% of the stations.

Table 4.23. Summary statistics for algal groups at Kure Atoll in 2006. Source: NWHI RAMP, unpub. data.

STATIASTICS	**MEAN**	**SD**	**FREQ**	**% FREQ**
Dictyosphaeria	10.42	19.8	4	50.00%
Halimeda	25	23.15	8	100.00%
Microdictyon	62.5	26.35	8	100.00%
Neomeris	0	0	0	0.00%
Jania	20.83	15.43	7	87.50%
Laurencia	43.75	37.73	6	75.00%
Non-geniculate branched coralline red algae	0	0	0	0.00%
Crustose coralline red algae	31.25	36.39	4	50.00%
Lobophora	30.21	27.44	7	87.50%
Padina	6.25	11.57	3	37.50%

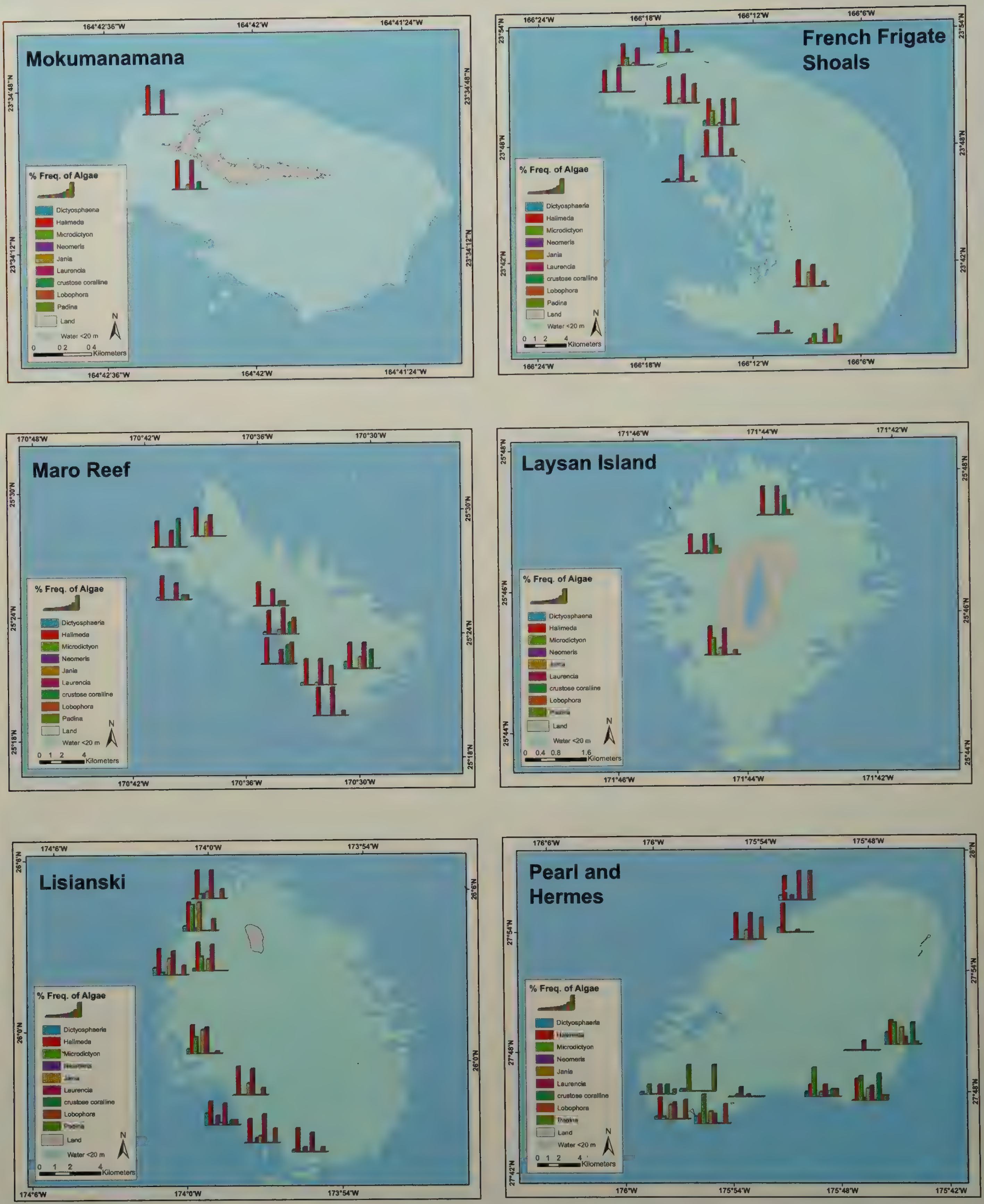


Figure 4.48. Percent frequency of occurrence of major algal groups by island in 2006. Source: NWHI RAMP, unpub. data; maps: L. Wedding.

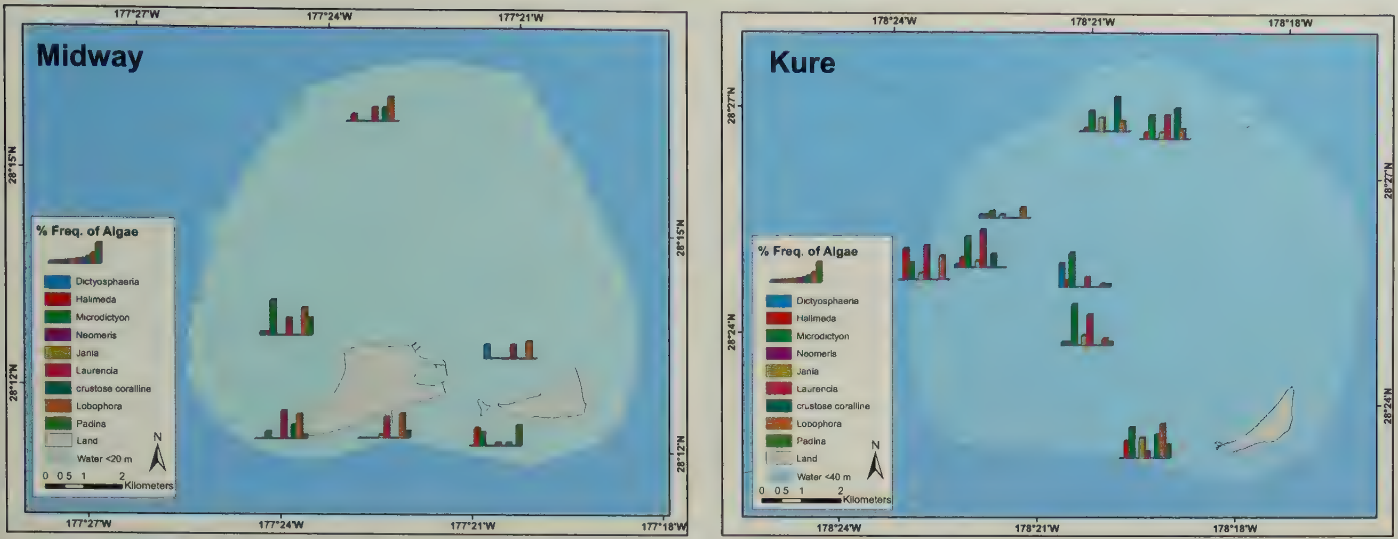


Figure 4.48 (continued). Percent frequency of occurrence of major algal groups by island in 2006. Source: NWHI RAMP, unpub. data; maps: L. Wedding.

INVERTEBRATES

Census of Coral Reef Ecosystems (CReefs)

The international CoML is a global effort to assess the diversity, distribution and abundance of ocean life and explain how it changes over time. Over 1,700 scientists from 73 countries are pooling their findings to create a comprehensive and authoritative portrait of life in the oceans today, yesterday and tomorrow. As one of 17 projects of the CoML, the goals of the CReefs are to increase tropical taxonomic expertise, conduct a taxonomically-diversified global census of coral reef ecosystems, and improve access to and unify coral reef ecosystem information scattered throughout the world.

As part of the CReefs effort, NOAA's Pacific Islands Fisheries Science Center Coral Reef Ecosystem Division led a multi-institutional team of international taxonomists on a 23-day research expedition in October 2006 to explore the biodiversity of small, understudied, or lesser known invertebrate, algal and microbial species at French Frigate Shoals. In an effort to maximize the ability to document biodiversity, surveys were conducted at over 50 different sites representing 14 habitat types using 12 diverse sampling methods (including baited traps, rubble brushing, rubble extraction, underwater vacuuming with gentle suction, plankton tows, light traps, sediment and water sampling) specifically designed to minimize habitat impacts while maximizing the number of ecological niches sampled.

During the three week cruise, scientists documented more than 1,000 species at French Frigate Shoals. For comparison, this corresponds to around 20% of the Hawaiian marine invertebrate fauna documented over the past 200 years. These new findings indicate just how little is known about tropical marine invertebrates in general and especially within the NWHI, and may offer clues to the extent of undiscovered diversity at French Frigate Shoals. Collected species were photo-documented for future study. Many species had never been photographed, fresh or alive, and thus represent the first documentation of their living color and appearance. DNA samples were also collected to facilitate DNA-based identification of Hawaiian and tropical Pacific invertebrates in the future.

Thorough taxonomic identifications and molecular analyses of the samples collected are still being analyzed and will take many years to complete. However, preliminary findings suggested that approximately 2,300 unique morpho-species were collected and photographed during the 16 days of sampling (Figure 4.50). To improve the long-term ability to monitor biodiversity, tissue samples for molecular barcoding were collected from about 60% of the unique morpho-species. An estimated 30-50 collected specimens are thought to be new species to science, including new species of crabs, corals, sea cucumbers, sea quirts, worms, sea stars, snails and clams. From this expedition, well over a hundred new species records from sponges, corals, anemones, flatworms, segmented worms, hermit crabs, crabs, sea slugs, bivalves, gastropods, octopus, sea cucumbers, sea stars and sea squirts, will likely be identified for French Frigate Shoals. The highest sampled diversities at French Frigate Shoals were in the phylums Anthropoda and Mollusca. By habitat type, lagoon patch reefs, La Perouse Pinnacle (basalt), back reef and deep fore reefs had the highest diversity. Due to the high level of taxonomic expertise available on the cruise, hand collection was the most effective sampling methodology, following by rubble extraction, rubble brushing and use of baited traps.

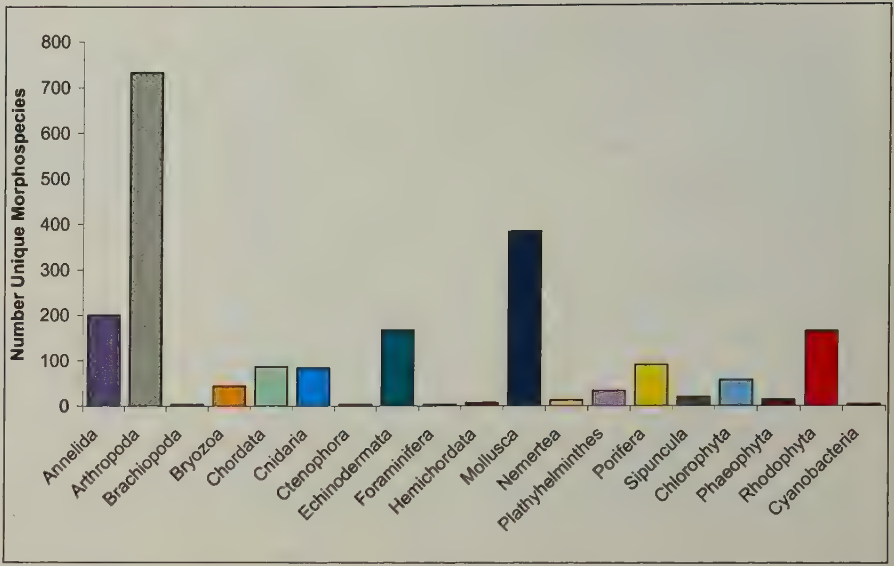


Figure 4.49. Unique morphospecies collected at French Frigate Shoals by phylum from CReefs cruise. Source: CoML, unpub. data.

Some anecdotal figures indicate the degree of novelty. For example, of the six specimens of octopus collected three species may be new to science (Figure 4.50). In comparison, 15 species of octopus were previously known from the Hawaiian Islands. Additionally, there were at least 25 species of sea cucumbers documented; three are new species and two are new records for Hawaiian fauna (Figure 4.50). Previously, about 30 species of shallow water holothurians have been documented from Hawaiian waters.

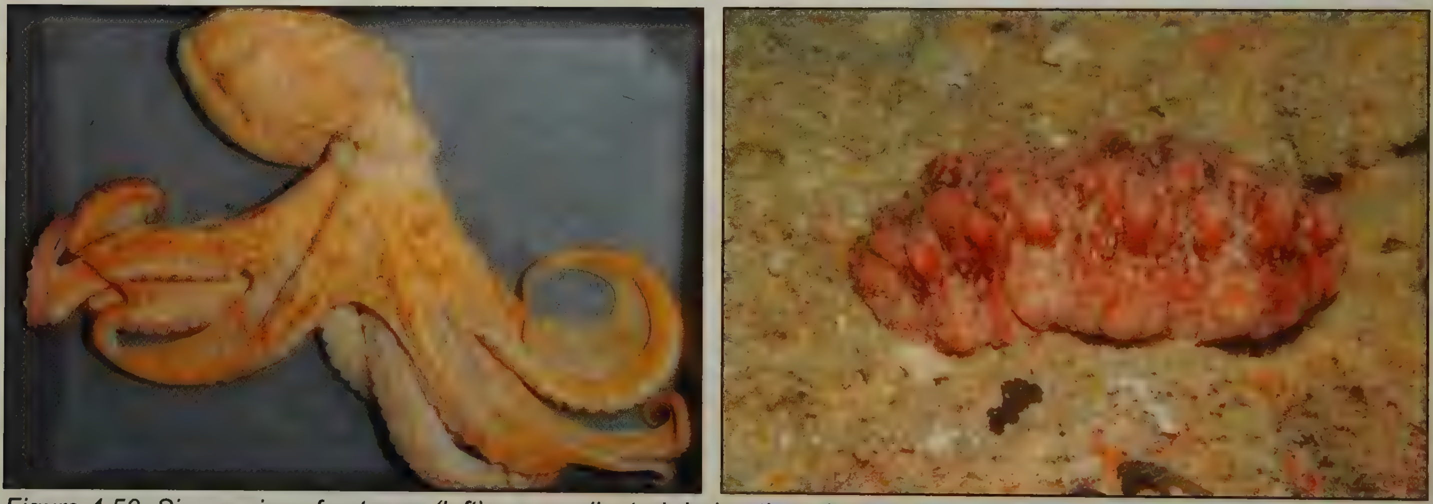


Figure 4.50. Six species of octopus (left) were collected during the mission, three of which may be new to science. The right photo shows a newly discovered species of sea cucumber. Photos: G. Paulay.

Though relatively high diversity was found for sponges, bryozoans, eulimid gastropods, hermit crabs, echinoderms, ascidians and other invertebrates (including corallimorph anemones, galatheid squat lobsters, porcellanid crabs, pea crabs and coral barnacles), had strikingly low diversity or were absent. Interestingly, about one third of all invertebrate morphospecies collected were either found only once or found at only one site. A possible new family of ascidian for the NWHI, Mogulidae, was collected. Likewise, a new species of coral that could not even be identified to family level was found and photographed, since coral collections were not authorized under this permit. An estimated 48 new species records of Opisthobranch molluscs for French Frigate Shoals were collected, 27 of which appear to be new records for the NWHI.

Other Invertebrate Surveys

Recent efforts to quantify the non-coral invertebrate populations in the NWHI included two broad-scale towed-diver surveys conducted in 2004 and 2006 (Figure 4.51) and a REA survey conducted in 2005. Surveys were focused on collecting information on three target classes of invertebrates: Echinoidea, Holothuroidea and Asteroidea. Towed-diver surveys found densities of echinoids and holothuroids to be highest at the northernmost

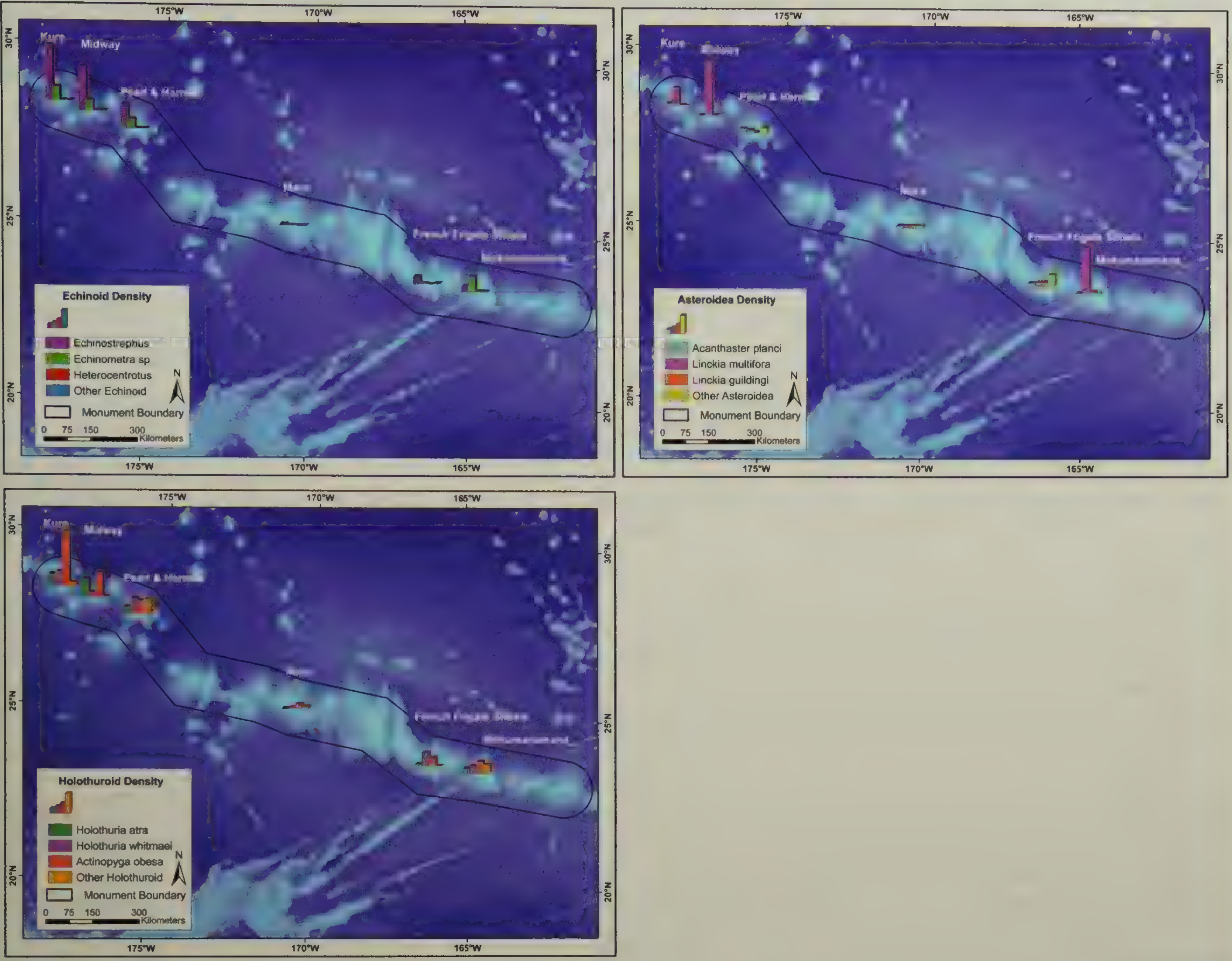


Figure 4.51 Mean density of Echinoids, Asteriods and Holothuroids per m^2 from towed diver surveys. Sources: NWHI RAMP, Brainard et al., in prep.; maps: L. Wedding.

islands/atolls. Sea urchins were the most common invertebrate observed during these surveys, with Kure (2004 and 2006) and Midway (2006) reporting the highest densities in the island chain (>1,600 urchins/ha). Sea cucumbers were present at all islands but in low densities, with the exception of the northern atolls. The highest sea cucumber density was recorded at Kure in 2006. COTS were in relatively low abundance throughout the archipelago with the highest density recorded in 2004 at Pearl and Hermes. Though abundance of COTS was relatively low in comparison with reported infestation levels in higher coral cover areas, such as the Great Barrier Reef, the impacts of these abundances could be significant due to the relatively low coral cover found throughout much of the NWHI.

Data collected during REA surveys included species level information on the three target classes of invertebrates and followed the general patterns of the towed-diver data. The most common echinoid throughout the NWHI was the burrowing sea urchin, *Echinostrephus* sp., with the highest densities recorded at Midway and Kure (>12 individuals/m^2). As in towed-diver surveys, sea cucumbers were present at all islands/atolls but in low densities. The most common sea cucumber was *Actinopyga obesa*, with a density of .03 individuals/ m^2 at Kure. The most common sea-star was *Linckia multifora*.

EXISTING DATA GAPS

Effective management decisions are based on reliable information on the biological characteristics of the organisms, their ecological relationships and understanding of the natural temporal variations that characterize their ecosystems. Overall there is a need for basic information on all living resources at the NWHI. Taxonomy studies should provide knowledge of all species presents to develop a baseline and facilitate identification of new species records and which ones are endemic, rare and worthy of special attention. Life history studies are needed to provide information on essential habitat requirements (reproduction, recruitment and feeding) for all life stages, environmental tolerance, larval dispersal mechanisms and other parameters (age structure, growth, mortality, etc.) for key native species. Specific research opportunities include:

- Developing a comprehensive catalog of native species that include: ecological requirements, georeferenced habitat use during different life stages, life history metrics (population age/size distributions, growth rates, size/age of maturity, mortality rates, etc.);
- Comparing native species habitats and ecological requirements to a catalog of anthropogenic threats in order to identify native species vulnerable to anthropogenic stress;
- Developing comparative life history studies between NWHI and MHI to determine anthropogenic effects on growth, maturation, and reproductive success of native species;
- Documenting the trophic dynamics of key native species;
- Developing a comprehensive species list of algal taxa for the NWHI;
- Determining habitat distribution/availability, especially that essential to reproduction, recruitment, and feeding;
- Characterizing the genetic structure of specific populations; and
- Determining the functional ecological roles of native species.

Monitoring programs require research to determine priority parameters and indicators to be measured for changes to ecosystems and ecological processes. Research also needs to indicate the scale, resolution and frequency of sampling that will contribute to meaningful monitoring, and the kinds of tools and technology that can best obtain the desired data. There are key gaps in the development and implementation of monitoring programs, including the need to determine:

- The variables, scale and the spatial and temporal resolution at which ecological processes and connectivity can be monitored to support management needs;
- The existing parameters and indicators of existing monitoring programs and identify gaps as the basis for more comprehensive monitoring of ecosystem change; and
- The spatial and temporal basis of ecological processes to identify ecological boundaries between subregions.

There are also key research issues that have been identified as important for monitoring and modeling, including:

- Which environmental conditions, e.g., temperature, flow, geomorphology, have a mitigating influence on survival in a changed environment;
- To what extent the reduction or expansion of one or more segments of the community assemblage result in competitive top down pressure or an increase in bottom up production;
- How ecosystem acclimation to change varies among taxa and in relation to both survival and the ability to effectively reproduce;
- The degree to which variability in an ecosystem may determine its capacity for resilience;

- How the rebound of an ecosystem depends on maintenance of established pathways of energy flow, which provide the system a stable means of recovery rather than risk a transition to a different state of equilibrium;
- To what extent reducing fish populations of the ecosystem undermine or realign energy flow and trophic stability;
- The other key aspects that affect ecosystem stability and resilience need to be identified, e.g., rates of energy flow, oceanographic conditions, nutrient levels and recruitment;
- The spatial and temporal patterns of plankton and larval dispersal, sources and sinks and
- The size, location and effectiveness of closed areas, e.g., MPAs.

As with monitoring of ecosystems and ecological processes, there is a need for research on the parameters and indicators most appropriate and practical for measuring changes to species populations and habitats. Research needs to address both marine terrestrial biodiversity and communities and seek to identify the scale, resolution and frequency of sampling that will contribute to meaningful monitoring of flora and fauna, as well as the most useful tools and technology for gathering the data. Important gaps in the development and implementation of monitoring programs include the need to determine:

- The variables, scale and the spatial and temporal resolution at which biodiversity and habitats should be monitored to support management needs;
- The existing parameters and indicators of existing monitoring programs and identify gaps as the basis for more comprehensive monitoring; and
- What spatial and temporal parameters distinguish sub-populations of species or differentiate habitats in the NWHI.

There are also specific research issues that have been identified as important for monitoring biodiversity and habitats, including the need to:

- Determine the priority species for monitoring in relation to anticipated short-term impacts, including from management actions, and long-term change;
- Document 'hot spots' of adult population abundance;
- Determine the movement of key species into the NWHI and within the NWHI;
- Assess priority species populations as a basis for monitoring and developing recovery models and projections of future population levels;
- Undertake life history studies for all priority species to provide information on essential habitat requirements (reproduction, recruitment and feeding) for all life stages;
- Determine essential habitat and ecological requirements of protected species to minimize anthropogenic threats and the effect of catastrophic events;
- Determine which likely effects of climate change on protected species are priorities for monitoring, e.g., the effect of sea level rise on nesting site of the green sea turtle and Hawaiian monk seal; and
- Evaluate exiting and potential diseases affecting priority species and habitats of the NHWI and develop appropriate methods to monitor the presence and impact of these on terrestrial and marine biodiversity.

APPENDIX

Distribution of corals and anemones reported in the NWHI during 1907-2006 compiled by Maragos from Dana (1846), Vaughan (1907), Dana (1971), Maragos et al. (2004), and the unpublished records of G. Aeby, J. Asher, J. Kenyon, J. Maragos, B. Vargas and B. Zgliczynski. Endemics in bold and asterisks (*) indicate undescribed species.

STONY CORALS	NIH	NEC	FFS	GAR	MAR	LAY	LIS	PHR	MID	KUR	N
*Coral unid., seen first by J. Starmer, sp.18			x								1
Acropora cerealis			x	x	x						3
A. cytherea		x		x	x	x		x			5
A. gemmifera			x	x							2
A. humilis			x	x	x						3
A. nasuta			x		x	x					3
A. paniculata			x								1
***A. sp.1 (prostrate)**			x				x				2
***A. sp.28 cf. retusa**			x								1
A. valida			x		x	x	x	x			5
***A. sp.29 (table)**			x								1
***A. sp.30 cf. palmerae**			x								1
A. sp. 20 (neoplasia/tumor?)			x								1
A. sp.26 cf. loripes			x								1
Montipora capitata	x	x	x	x	x	x	x	x	x	x	11
M. flabellata		x	x	x	x	x	x	x	x	x	9
M. patula	x	x	x	x	x	x	x	x	x	x	10
***M. sp.4 cf. incrassata**		x	x		x					x	4
M. dilatata						x	x				2
***M. sp.6 cf. dilatata**					x						1
***M. sp.7 (foliaceous)**			x				x	x	x		4
***M. sp.2 (ridges)**								x		x	2
***M. sp.5 (branching)**							x				1
***M. sp.14 (nodular) first** seen by B. Vargas								x			1
M. tuberculosa			x		x	x	x	x	x	x	7
***M. sp.24 (irregular)**			x								1
***M. sp.3 cf. turgescens**					x	x	x	x	x	x	6
M. verrilli			x		x	x	x	x	x	x	7
Gardineroseris planulata									x		1
Leptoseris hawaiiensis			x			x					2
L. incrustans			x					x	x	x	4
***L. sp.22 cf. incrustans**			x								1
L. mycetoseroides			x								1
***L. cf. papyracea sp19**			x								1
***L. cf. scabra sp17**			x				x				2
Pavona clavus								x	x	x	3
P. duerdeni	x	x	x	x	x	x	x	x	x	x	10
P. maldivensis			x		x		x	x	x	x	6
P. varians	x	x	x	x	x	x	x	x	x	x	10
**Balanophyllia* sp. (pink)			x		x					x	3
Cladopsammia eguchii			x	x	x	x		x	x	x	7
Tubastraea coccinea	x		x	x	x	x		x	x	x	9
Cyphastrea ocellina	x	x	x	x	x	x	x	x	x	x	10
Leptastrea agassizi			x		x				x		3
L. bewickensis			x				x	x			3
L. purpurea	x	x	x	x	x	x		x	x	x	9
L. pruinosa		x	x	x	x						4
***L. sp.8 cf. F. hawaiiensis**		x	x		x		x			x	5
**Cycloseris tenuis*			x	x			x	x			4
**C. vaughani*			x				x	x	x		4
Diaseris distorta			x				x				2

Continued from previous page, distribution of corals and anemones reported in the NWHI during 1907-2006 compiled by Maragos from Dana (1846), Vaughan (1907), Dana (1971), Maragos et al. (2004), and the unpublished records of G. Aeby, J. Asher, J. Kenyon, J. Maragos, B. Vargas and B. Zgliczynski. Endemics in bold and asterisks (*) indicate undescribed species.

STONY CORALS	**NIH**	**NEC**	**FFS**	**GAR**	**MAR**	**LAY**	**LIS**	**PHR**	**MID**	**KUR**	**N**
Fungia scutaria	x		x	x	x	x	x	x	x	x	9
F. granulose					x	x		x			3
Pocillopora damicornis			x		x	x	x	x	x	x	8
P. eydouxi	x	x	x	x	x	x	x	x	x		9
P.* sp.10 cf. *laysanensis			x			x				x	4
P. ligulata	x	x	x	x	x	x	x	x	x	x	11
P. meandrina	x	x	x	x	x	x	x	x	x	x	10
P. molokensis	x		x	x	x	x	x	x		x	9
P.* sp.32 cf. *verrucosa			x				x	x			3
P. sp.33 cf. *zelli*			x								1
**P.* sp.11 cf. *capitata*			x		x	x	x	x	x	x	8
****Porites* sp.12 cf. *annae***							x	x		x	3
****P.* sp. 15 (paliform lobes)**			x								1
Porites brighami	x	x	x	x	x	x	x	x		x	9
P. compressa	x	x	x	x	x	x	x	x	x	x	11
****P.* sp.23 (arthritic fingers)**			x								1
P. duerdeni		x	x	x	x			x		x	6
P. evermanni	x	x	x	x	x	x	x	x	x	x	10
P. hawaiiensis		x	x		x	x	x	x	x	x	8
P. lobata	x	x	x	x	x	x	x	x	x	x	10
****P.* sp. 21 cf. *lobata***			x								1
****P.* sp.16 cf. *lutea***			x								1
P. rus					x						1
****P.* sp.27 (columns)**			x								1
****P.* sp.13 cf. *solida***			x	x		x		x	x	x	6
Psammocora explanulata				x							1
P. nierstraszi		x	x	x	x	x	x	x	x		8
P. stellata	x		x	x	x	x	x	x	x	x	10
P. verrilli								x	x	x	3
Total	**17**	**21**	**66**	**29**	**41**	**34**	**37**	**43**	**33**	**36**	
Endemic	**4**	**8**	**27**	**7**	**12**	**11**	**15**	**14**	**8**	**15**	**Mean**
Percent endemic	**23.5**	**38.1**	**40.9**	**24.1**	**29.3**	**32.3**	**40.5**	**32.6**	**24.2**	**41.7**	**32.8**

Non-stony corals and anemones.

Non-Stony Corals & Anemones	**NIH**	**MMM**	**FFS**	**GAR**	**MAR**	**LAY**	**LIS**	**PHR**	**MID**	**KUR**
Palythoa tuberculosa	x	x	x	x	x	x	x	x	x	x
P. sp.			x							
Zoanthus pacificus			x		x			x		x
Zoanthus sp (Kure)										x
Zoanthus sp ("B")	x	x	x		x		x			
**Sinularia* sp (yellow)	x	x	x	x			x			
**Sinularia* (purple)				x						x
**Sinularia* (brown)			x							
**Sinularia* (pink)								x		
Acabaria bicolor			x							x
Cirrhipathes sp	x		x							
Heteractis malu			x	x	x	x				x
Total Species Per Island	**4**	**3**	**9**	**4**	**4**	**2**	**3**	**3**	**1**	**6**

REFERENCES

Aeby, G.S. 1998. A digenean metacercaria from the reef coral, Porites compressa, experimentally identified as *Podocotyloides stenometra*. Journal of Parasitology 84:1259-1261.

Aeby, G.S. 2006. Baseline levels of coral disease in the Northwestern Hawaiian Islands. Atoll Research Bulletin 543:471-488.

Aeby, G.S. 2006b. Outbreak of coral disease in the Northwestern Hawaiian Islands. Coral Reefs 24(3): 481.

Aeby, G.S. 2007. Spatial and temporal patterns of infection of Porites trematodiasis on the reefs of Kaneohe Bay, Oahu, Hawaii. Bull. Mar. Sci. 80(1): 209-218.

Brainard, R.E., E. DeMartini, J. Kenyon, P. Vroom, J. Miller, R. Hoeke, J. Rooney, R. Schroeder, and M. Lammers. 2004. Multi-disciplinary spatial and temporal monitoring of reef ecosystems of the US-affiliated Pacific Islands. 10th Int.Coral Reef Symp. Okinawa.

Brainard, R.E., et al. in prep. Coral reef ecosystem monitoring report for the Hawaiian Archipelago, 2000-2008. NOAA Special Report NMFS PIFSC.

Cheney, D.F. 1977. RandC/P, a new and improved ratio for comparing seaweed floras. Journal of Phycology 13 (Supplement): 12.

Dana, J.D. 1846. Zoophytes. Vol. VII. United States Exploring Expedition during the years 1838, 1839, 1840, 1841, 1842 under the command of Charles Wilkes, U.S.N. C. Sherman Printer, Philadelphia, Pennsylvania.

Dana, T.F. 1971. On the reef corals of the world's most northern atoll (Kure: Hawaiian Archipelago). Pac. Sci. 25:80-87.

DeMartini, E.E. and A.M. Friedlander. 2004. Spatial pattern of endemism in shallow water reef fish populations of the Northwestern Hawaiian Island. Mar. Ecol. Prog. Ser. 271:281-296.

DeMartini, E.E. and A.M. Friedlander. 2006. Predation, endemism, and related processes structuring shallow-water reef fish assemblages of the Northwestern Hawaiian Islands. Atoll Research Bulletin 543:237-256

Fenner, D. 2005. Corals of Hawaii. Mutual Publishing, Honolulu. 143 pp.

Friedlander, A., G. Aeby, R. Brainard, A. Clark, E. DeMartini, S. Godwin, J. Kenyon, R. Kosaki, J. Maragos, and P. Vroom 2005. *The state of coral reef ecosystems of the Northwestern Hawaiian Islands*. The state of coral reef ecosystems of the United States and Pacific freely associated states, 270–311.

Green, E. and A. Bruckner. 2000. The significance of coral disease epizootiology for coral reef conservation. Biological Conservation 96: 347-361.

Grigg, R.W. 1982. Darwin Point: a threshold for atoll formation. Coral Reefs 1: 29-34.

Grigg, R.W. 1983. Community structure, succession and development of coral reefs in Hawaii. Mar Ecol Prog Ser 11:1-14.

Grigg, R.W. 1997. Paleoceanography of coral reefs in the Hawaiian-Emperor Chain – Revisited. Coral Reefs 16, Suppl: S33-S38.

Grigg, R. W., J. Polovina, A. Friedlander, and S. Rohman. 2008. Biology and paleoceanography of the coral reefs in the northwestern Hawaiian Islands. In: Coral reefs of the United States (B. Riegl and R. Dodge, eds.). Springer-Verlag Publishing.

Grigg, R.W., J. Wells and C. Wallace. 1981. Acropora in Hawaii. Part 1. History of the scientific record, systematics and ecology. Pac Sci 35:1-13.

Harvell, C., K. Kim, J. Burkholder, R. Colwell, P. Epstein, D. Grimes, E. Hofmann, E. Lipp, A. Osterhaus, R. Overstreet, J. Porter, G. Smith, and G. Vasta. 1999. Emerging marine diseases-Climate links and anthropogenic factors. Science 285:1505-1510.

Harvell, C.D., C.E. Mitchell, J.R. Ward, S. Altizer, A.P. Dobson, R.S. Ostfeld, and M.D. Samuel. 2002. Climate warming and disease risks for terrestrial and marine biota. Science:296 :2158–2162.

Hoeke, R.K., R. Brainard, R. Moffitt, G. Liu, A. Strong, W. Skirving, and J. Kenyon. 2005. Oceanographic conditions implicated in the 2002 Northwestern Hawaiian Islands coral bleaching event. Abstract, p. 90. In: 10th Int. Coral Reef Symposium, Okinawa.

Hunter, C. and C. Evans. 1995. Coral reefs in Kaneohe Bay, Hawaii: two centuries of western influence and two decades of data. Bull. Mar. Sci. 57(2):501-515.

Jacobson, D.M. 2006. Fine scale temporal and spatial dynamics of a Marshall Islands coral disease outbreak: evidence for temperature forcing. Abstract. Ocean Sciences Meeting, Honolulu, HI.

Kenyon, J.C., G.S. Aeby, R.E. Brainard, J.D. Chojnacki, M.J. Dunlap, and C.B. Wilkinson. 2006. Mass coral bleaching on high-latitude reefs in the Hawaiian Archipelago. Proceedings of the 10th International Coral Reef Symposium Okinawa 2: 631-643.

Kenyon J.C. and R.E. Brainard. 2006. Second recorded episode of mass coral bleaching in the Northwestern Hawaiian Islands. Atoll Research Bulletin 543: 505-523.

Kenyon, J.C., Brainard, R.K. Hoeke, F.A. Parrish, and C.B. Wilkinson. 2006a. Towed-diver surveys, a method for mesoscale spatial assessment of benthic reef habitat: a case study at Midway Atoll in the Hawaiian Archipelago. Coastal Management 34(3): 339-349.

Kenyon, J.C., M.J. Dunlap, and G.S. Aeby. 2008a. Community structure of hermatypic corals at Kure Atoll in the Northwestern Hawaiian Islands: stemming the shifting baseline. Atoll Research Bulletin.

Kenyon, J.C., M.J. Dunlap, C.B. Wilkinson, K.N. Page, P.S. Vroom, and G.S. Aeby. 2007a. Community structure of hermatypic corals at Pearl and Hermes Atoll, Northwestern Hawaiian Islands: unique conservation challenges in the Hawaiian Archipelago. Atoll Research Bulletin 549: 1-23.

Kenyon, J.C., C.B. Wilkinson, M.J. Dunlap, G.S. Aeby, and C. Kryss. 2007b. Community structure of hermatypic corals at Laysan Island and Lisianski Island/Neva Shoal in the Northwestern Hawaiian Islands: a new layer of scientific exploration. Atoll Research Bulletin 550: 1-28

Kenyon, J.C., C.B. Wilkinson, and G.S. Aeby. 2008b. Community structure of hermatypic corals at Maro Reef in the Northwestern Hawaiian Islands: a unique open atoll. Atoll Research Bulletin.

Maragos, J.E. and P.L. Jokiel 1986. Reef corals of Johnston Atoll: One of the world's most isolated reefs. Coral Reefs 4: 141-150.

Maragos, J., C. Evans, and P. Holthus. 1985. Reef corals in Kaneohe Bay six years before and after termination of sewage (Oahu, Hawaiian Archipelago). Pp: 189-194. In: Proc. 5th Intl. Coral Reef Congress, Tahiti, 4.

Maragos, J.E., D.C. Potts, G.S. Aeby, D. Gulko, J.C. Kenyon, D. Siciliano, and D. VanRavenswaay. 2004. 2000-2002 Rapid Ecological Assessments of corals (Anthozoa) on shallow reefs of the Northwestern Hawaiian Islands. Part 1: species and distribution. Pacific Science 58(2): 211-230.

Miller, M., A. Bourgue, and J. Bohnsack 2002. An analysis of the loss of acroporid corals at Looe Key, Florida US: 1983-2000. Coral Reefs 21:179-182.

Page, K.N. 2006. Factors influencing benthic distributional patterns in a near-pristine coral reef ecosystem: Pearl and Hermes Atoll. Master's Thesis, University of Hawaii, Honolulu.

Patterson, K.L., J.W. Porter, K.B. Ritchie, S.W. Polson, E. Mueller, E.C. Peters, D.L. Santavy and G.W. Smith. 2002. The etiology of white pox, a lethal disease of the Caribbean elkhorn coral, *Acropora palmata*. Proceedings of the National Academy of Sciences of the United States of America 99:8,725-8,730.

PIFSC-CRED, Honolulu, Hawaii.

Porter, J., P. Dustan, W. Jaap, K. Patterson, V. Kosmynin, O. Meier, M. Patterson, and M. Parsons 2001. Patterns of spread of coral disease in the Florida Keys. Hydrobiologia 460: 1-14.

Randall, J.E. 2007. Reef and shore fishes of the Hawaiian Islands. Bull. Mar. Sci. 41:490-502.

Rohmann, S.O., J.J. Hayes, R.C. Newhall, M.E. Monaco, and R.W. Grigg. 2005. The area of potential shallow-water tropical and subtropical coral ecosystems in the United States. Coral Reefs 24:370-383.

Siciliano D. 2005. Latitudinal limits to coral reef accretion: Testing the Darwin Point Hypothesis at Kure Atoll, Northwestern Hawaiian Islands, using new evidence from high resolution remote sensing and in situ data. Ph.D. Dissertation, University of California, Santa Cruz, 30-154.

Sutherland, K., J. Porter, and C. Torres 2004. Disease and immunity in Caribbean and Indo-Pacific zooxanthellate corals. Marine Ecol Progress Series 266: 273-302.

Vaughan, T. F. 1907. Recent Madreporaria of the Hawaiian Islands and Laysan. Bull. U.S. Natl. Mus. 59:1-427.

Veron, J.E.N. 1995. Corals in space and time. Cornell University Press, Ithaca, NY. 321 pp.

Vroom, P.S. and K.N. Page 2006. Relative abundance of macroalgae (RAM) on Northwestern Hawaiian Island reefs. Atoll Research Bulletin 543: 533-548.

Vroom, P.S., K.N. Page, J.C. Kenyon, and R.E. Brainard. 2006. Algae-Dominated Reefs. American Scientist 94: 429-437.

Weil, E. 2004. Coral reef diseases in the wider Caribbean. Pp: 35-68. In E. Rosenberg and Y. Loya (eds). Coral Health and Disease. Springer-Verlag, Germany.

Weil, E., G. Smith, and D. Gil-Agudelo. 2006. Status and progress in coral reef disease research. Dis Aquat Org 69: 1-7.

Willis, B., C. Page, and E. Dinsdale 2004. Coral disease on the Great Barrier Reef. Pp: 69-104. In: E. Rosenberg and Y. Loya (eds). Coral Health and Disease. Springer-Verlag, Germany.

PERSONAL COMMUNICATIONS

Maragos, J.E. U.S. Fish and Wildlife Service, Honolulu, HI, U.S.A.

Fishes

Alan Friedlander[1,2], Edward DeMartini[3], Lisa Wedding[1,4] and Randy Clark[1]

BIOGEOGRAPHY OF FISHES

The Hawaiian Archipelago is among the most isolated on earth and exhibits the highest level of marine fish endemism of any archipelago in the Pacific (Randall, 1995, 1998, 2007; Randall and Earle, 2000; Allen, 2002). Owing to limited human influence, the Northwestern Hawaiian Islands (NWHI) reefs are nearly pristine and represent one of the last remaining intact large-scale, predator-dominated coral reef ecosystems on earth (Friedlander and DeMartini, 2002). Because of its high level of endemism and the near pristine nature of its reefs, the NWHI represents an important global biodiversity hot spot and provides a view of what reefs in the MHI may have looked like before human contact.

Despite centuries of exploitation, the MHI today has even higher biodiversity of fishes than the NWHI. Randall et al. (1993) reported 258 species of reef and shore fishes from Midway Atoll compared with 612 species in the MHI (Randall, 2007). Mundy (2005) lists 21 species that are known from the NWHI, but not the MHI (Table 5.1). Of these, most are either deep-water or mesopelagic and therefore poorly sampled waifs, or species with poor taxonomic resolution. In contrast, 406 species are known from the Main Hawaiian Islands (MHI) but not the NWHI and overall richness and diversity are greater in the MHI compared with the NWHI (Mundy, 2005).

Table 5.1. Fish species known from the NWHI but not found in the MHI. Source: Mundy, 2005.

FAMILY	SPECIES	COMMON NAME	LOCATIONS	HABITAT
Scyliorhinidae	*Apristurus spongiceps*	Spongehead catshark	Nihoa	Deep-water
Muraenidae	*Gymnothorax atolli*	Atoll moray	Pearl and Hermes to Midway	Cryptic
Platytroctidae	*Mentodus mesalirus*	Tubeshoulders	Pearl and Hermes to Midway	Deep-water
Stomiidae	*Astronesthes nigroides*	Dragonfish	Pearl and Hermes to Midway	Mesopelagic
	Eustomias cancriensis	Scaleless black dragonfish	Pearl and Hermes to Midway	Mesopelagic
Ophidiidae	*Bassozetus zenkevitchi*	Cusk-eel	Midway to Kure	Deep-water
	Spectrunculus grandis	Cusk-eel	Maro	Deep-water
Macrouridae	*Cetonurus crassiceps*	Grenadier, Rattail	Pearl and Hermes	Deep-water
Holocentridae	*Myripristis murdjan*	Blotcheye soldierfish	Midway to Kure	Shallow reefs
Fistulariidae	*Fistularia petimba*	Serrate coronetfish	Nihoa to Kure	Mod-deep-water
Laysan	*Scorpaenopsis pluralis*	Laysan scorpionfish	Lasyan	Deep-water
Callanthiidae	*Grammatonotus macrophthalmus*	Splendid perch	French Frigate Shoals	Deep-water
Epigonidae	*Epigonus devaneyi*	Deepwater cardinalfish	Mokumanamana to Maro	Deep-water
Carangidae	*Caranx lugubris*	Black trevally	Mokumanamana to Midway	Shallow to deep
Carangidae	*Decapterus macrosoma*	Shortfin scad	Maro	Pelagic
Pomacanthidae	*Centropyge interruptra*	Japanese angelfish	Kure and Midway	Shallow reefs
Kyphosidae	*Girella leonina*	Blackedge nibbler	Midway	Waif
Labridae	*Epibulus insidiator*	Slingjaw wrasse	French Frigate Shoals north to Kure	Shallow reefs
Ammodytidae	*Lepidammodytes macrophthalmus*	Sand lance	Maro	Poorly known
Ephippidae	*Platax boersii*	Boer's spadefish	Midway	Waif
Luvaridae	*Luvarus imperialis*	Louvar	Laysan	Epipelagic

---

1. NOAA/NOS/NCCOS/CCMA Biogeography Branch
2. The Oceanic Institute
3. NOAA/NMFS/Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division
4. University of Hawaii at Manoa

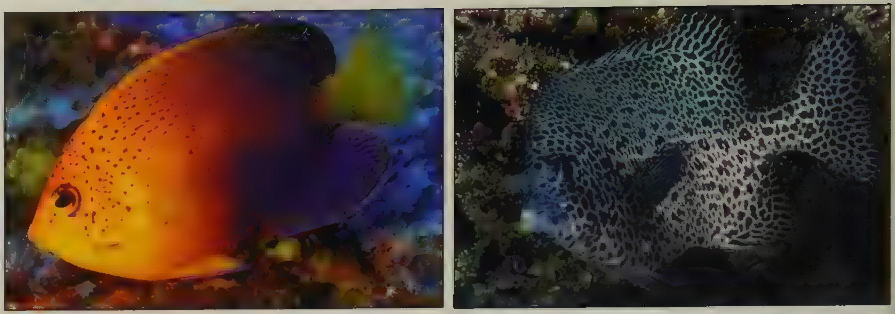


*Figure 5.1. The Japanese angelfish (*Centropyge interruptra*; left) and the spotted knifejaw (*Oplegnathus punctatus*; right) are known only from the NWHI and Japan, although the latter is occasionally observed in the MHI. Photo: J. Watt.*

The few demersal species found in the NWHI but not the MHI include the blotcheye soldierfish (*Myripristis murdjan*), an Indo-Pacific species but restricted to the NWHI in the Hawaiian archipelago, and the Japanese angelfish (*Centropyge interruptra*; Figure 5.1) which is known only from the NWHI and Japan (Mundy, 2005). Evidence of larval pelagic transport from Japan to the NWHI via the Kuroshio and North Pacific Currents is supported by the presence of a number of species that are common only off Japan and the northwestern end of the Hawaiian Archipelago (Randall, 2007). In addition to the Japanese angelfish, these include two lizardfishes (*Synodus lobelia* and *S. ulae*), the manyspine squirrelfish (*Sargocentron spinosissimum*), two species of knifejaws (*Oplegnathus fasciatus* and *O. punctatus*) and the blackedge nibbler (*Girella punctata , family Girellidae*), a close relative of the chubs of the family Kyphosidae (Randall, 2007).

Two species, the slingjaw wrasse (*Epibulus insidiator*) and the chevron butteryflyfish (*Chaetodon trifascialis*), are associated with *Acropora* corals that occur only in the central portion of the NWHI, and although these fish species are occasionally observed in the MHI and the far northern end of the chain, they are most abundant from French Frigate Shoals to Pearl and Hermes (Mundy, 2005). Despite the taxonomic similarity with the MHI fauna, the NWHI fish assemblage differs from that of the MHI at various ecological and demographic levels owing to oceanographic conditions (e.g., water temperature), habitat (e.g., coral and reef type) and anthropogenic influences (e.g., effects of fishing in the MHI).

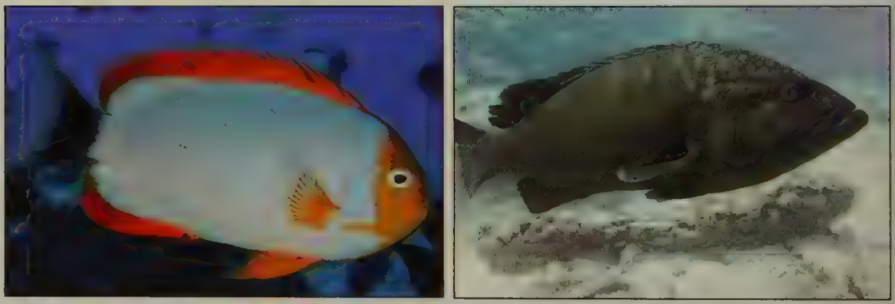


*Figure 5.2. The endemic masked angelfish (*Genicanthus personatus*, left) and Hawaiian grouper (*Epinephelus quernus*, right) are found in shallower water at Midway Atoll but are restricted to deeper depths in the MHI. Photos: J. Watt (left); J. Maragos (right).*

There are a variety of environmental and other reasons for lower reef fish diversity in the NWHI versus MHI. Many shallow-water fish species that are adapted to warmer water cannot survive in the NWHI since winter water temperatures can be as much as 7ºC cooler than the MHI (Mundy, 2005). Some shallow-water species are adapted to cooler water and can be found in deeper waters at the southern end of the archipelago. This phenomenon known as tropical submergence is exemplified by species such as the yellowfin soldierfish (*Myripristis chryseres*), the endemic Hawaiian grouper (*Epinephelus quernus*), and the masked angelfish (*Genicanthus personatus*), all of which occur in shallow water at Midway but are restricted to much greater depths in the MHI (Figure 5.2; Randall et al., 1993; Mundy, 2005). Other reasons for the lower number of species in the NWHI include insufficient sampling effort and the lack of many high island habitats such as estuaries and rocky shorelines

Some of the non-endemic species abundant at higher latitude reefs in the NWHI have antitropical distributions and are thought to have established themselves in the archipelago when surface waters were previously cooler (Randall, 1981). The Hawaiian morwong, (*Goniistius vittatus*) for example, may be a cryptic species that diverged during the late Miocene-early Pliocene from the lineage presently represented by nominal conspecifics in the southern hemisphere (Burridge and White, 2000). Interestingly, most Hawaiian endemic species do not appear to exhibit submergence (greater depth distributions) in the MHI, although rigorous comparisons are lacking (DeMartini and Friedlander, 2004).

Fish Species Richness

Despite lower species richness in the NWHI as compared with the MHI (Mundy 2005), the total number of species (210) observed on quantitative transects in the NWHI (DeMartini and Friedlander, 2004) was similar to the number of species (215) reported in a recent comprehensive quantitative study around the MHI (Friedlander et al., 2007). The lowest overall fish species richness in the NWHI occurs at the small basalt islands (Mokumanamana, Gardner and Nihoa; Figure 5.3) and highest at French Frigate Shoals and Pearl and Hermes. The former may be related to the higher coral richness and greater diversity of habitats (Maragos et al., 2004), while the latter is likely related to large size, habitat diversity and presence of subtropical and temperate species which occur at much greater depths southward in the chain of islands.

Total species richness observed on surveys (y) showed a positive, linear relationship ($y=8.05 * \ln(x+1) + 112.2$, $R^2=0.51$, $p=0.02$, Table 5.2, Figure 5.4) with a logarithmic function of total reef area less than 10 fathoms (x). This relationship is consistent with the general theory of island biogeography and likely reflects the greater diversity of habitats present in larger reef areas.

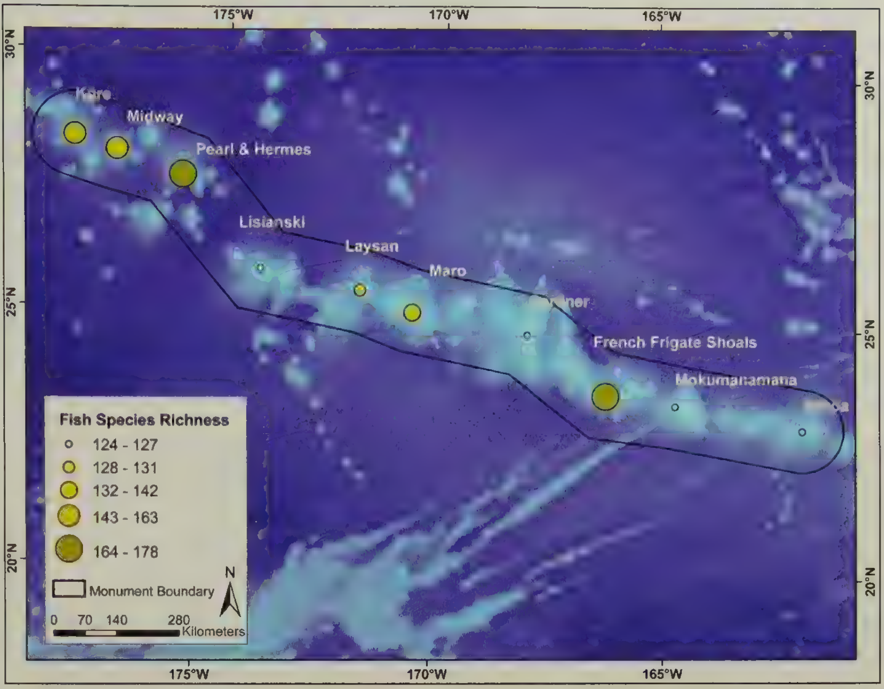


Figure 5.3. Total fish species richness at each of 10 emergent NWHI reefs. Source: NWHI RAMP, unpub. data; map: L. Wedding.

Table 5.2. Results of least squares linear regression model for total number of species by ln (total reef area within 10 fathoms +1). $R^2 = 0.51$, N = 10. Source: NWHI RAMP, unpub. data.

ANALYSIS OF VARIANCE				
Source	**DF**	**Mean Square**	**F Ratio**	**Prob > F**
Model	1	2105.32	8.20	0.0211
Error	8	256.85		
C. Total	9			
PARAMETER ESTIMATES				
Term	**Estimate**	**Standard Error**	**t Ratio**	**Prob>|t|**
Intercept	112.21	12.3	9.12	<0.001
Ln (area)	8.052	2.81	2.86	0.0211

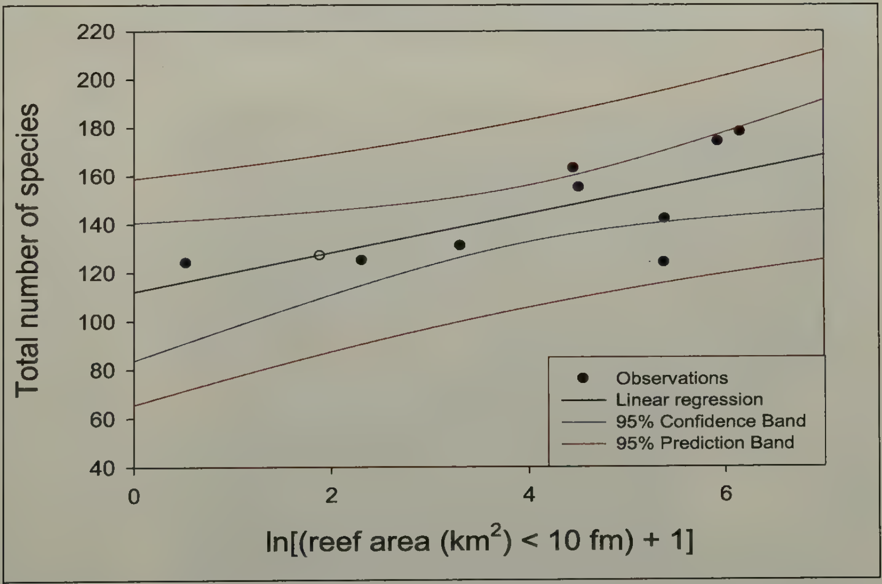


Figure 5.4. Relationship between cumulative number of fish species at each reef and total reef area (km^2) within 10 fathoms. Source: Friedlander et al., in prep.

Endemism

The Hawaiian Island chain is among the most isolated on earth and exhibits the highest level of marine fish endemism of any archipelago in the Pacific (Randall, 1995, 1998; Randall and Earle, 2000; Allen, 2002). Endemism is a key attribute of biotic communities that is generally a great concern of conservation ecology. One reason of general biogeographic interest is that speciation and the origin and maintenance of biodiversity are undoubtedly related to degrees of isolation and endemism (Gray, 1997). Because of the decline in global marine biodiversity, endemic "hot spots" like Hawaii are important areas for global biodiversity conservation. The endemic fishes of Hawaii are small bodied and have very restricted geographic ranges of less than 50,000 km^2 (Roberts et al., 2002). Small body size, per se, may be associated with higher extinction risk because small-bodied species tend to have narrower habitat requirements (Hawkins et al., 2000). Therefore both body size and endemic status argue for the conservation of these species.

Based on species-presence, endemism is equivalent for fishes in the NWHI (20.6% using all available data) and the MHI (MHI, 20.9%; DeMartini and Friedlander, 2004). On average, percentage endemism was much higher based on numerical densities (52%) and biomass (37%) which increased with latitude, and was especially pronounced at the four northernmost reefs that are the oldest emergent geological features of the archipelago (Figure 5.5). Greater endemism towards Midway and Kure appears related to consistently higher rates of replenishment by young-of-the-year (YOY) upchain following dispersal as pelagic larvae and/or juveniles. There were significant positive relationships between number and biomass of endemics with latitude (Tables 5.3, 5.4, 5.5; Figures 5.6). However endemism based on species presence was not significantly correlated with latitude (Figure 5.7).

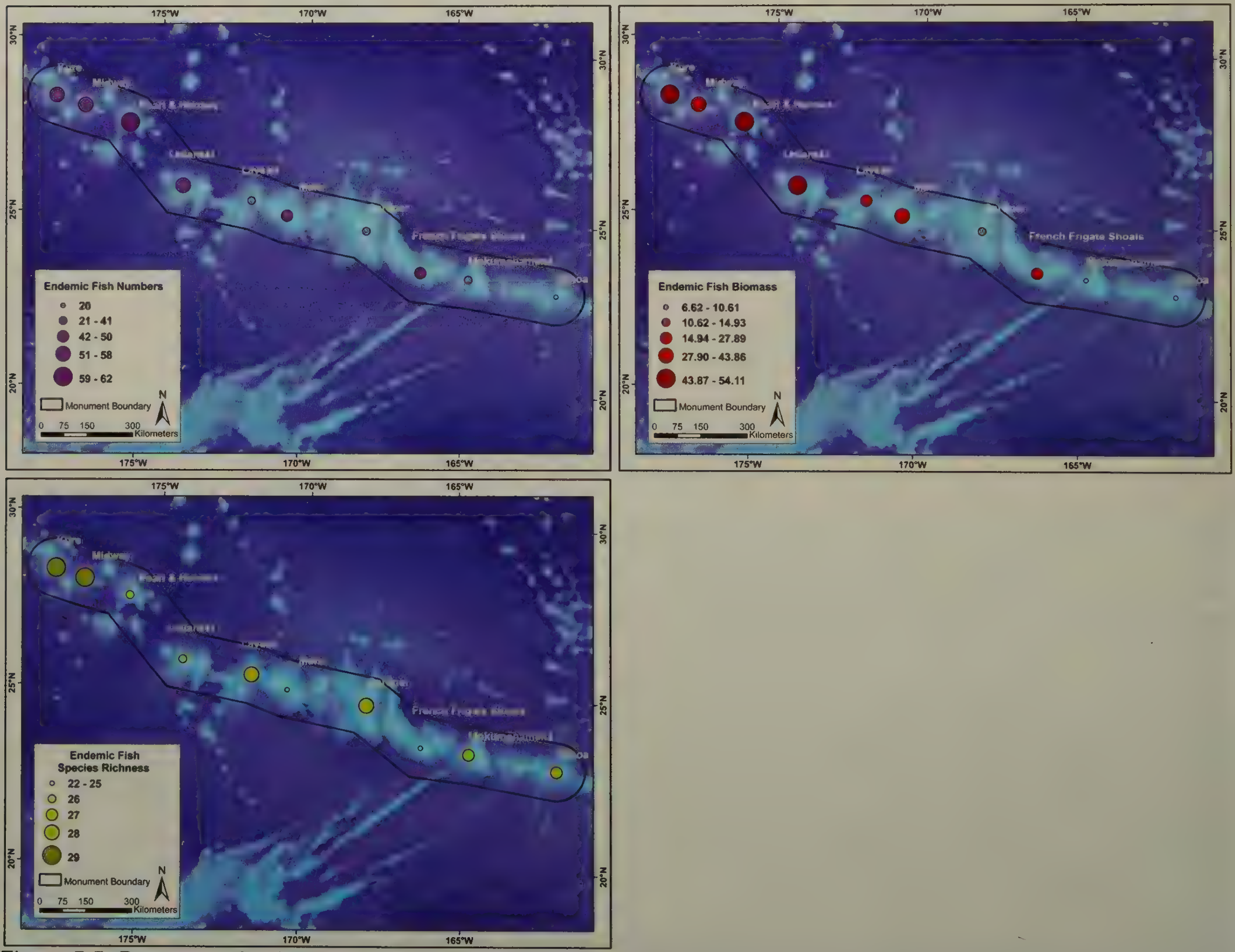


Figure 5.5. Percent endemism based on numerical densities (top left), biomass (top right) and species richness (bottom left) at each of 10 emergent NWHI reefs. Source: DeMartini and Friedlander, 2004; maps: L. Wedding.

Endemic reef fishes are appreciably smaller bodied than nonendemics within the NWHI (DeMartini and Friedlander, 2004). Median body size does not vary with latitude and longitude for either endemics or nonendemics, which obviates possibly confounding environmental effects. Reef fish populations at higher latitude reefs included larger proportions of YOY recruits. YOY length frequencies did not differ for most species between northern and southern reefs, suggesting that a seasonal lag in spawning and recruitment at higher latitudes cannot explain the greater YOY densities observed. Disproportionate recruitment at higher-latitude reefs may be related to better growth and survivorship after settlement onto reefs, higher levels of within-reef and regional reseeding at higher latitudes, or other factors.

Table 5.3. Results of least squares linear regression model for total number of species by ln (total reef area within 10 fathoms +1). $R^2 = 0.51$, N = 10. Source: DeMartini and Friedlander, 2004.

ANALYSIS OF VARIANCE				
Source	**DF**	**Mean Square**	**F Ratio**	**Prob > F**
Model	1	962.8	15.86	0.004
Error	8	60.72		
C. Total	9			
PARAMETER ESTIMATES				
Term	**Estimate**	**Standard Error**	**t Ratio**	**Prob>|t|**
Intercept	-89.86	34.15	-2.63	0.0301
Latitude	5.28	1.32	3.98	0.004

Table 5.4. Results of least squares linear regression model for total number of species by ln (total reef area within 10 fathoms +1). $R^2 = 0.51$, N = 10. Source: DeMartini and Friedlander, 2004.

ANALYSIS OF VARIANCE				
Source	**DF**	**Mean Square**	**F Ratio**	**Prob > F**
Model	1	1817.66	14.7374	0.005
Error	8	123.34		
C. Total	9			
PARAMETER ESTIMATES				
Term	**Estimate**	**Standard Error**	**t Ratio**	**Prob>|t|**
Intercept	-153.734	48.67219	-3.16	0.0134
Latitude	7.249942	1.888528	3.84	0.005

Table 5.5. Results of least squares linear regression model for total number of species by ln (total reef area within 10 fathoms +1). $R^2 = 0.51$, N = 10. Source: DeMartini and Friedlander, 2004.

ANALYSIS OF VARIANCE				
Source	**DF**	**Mean Square**	**F Ratio**	**Prob > F**
Model	1	8.18	3.53	0.0971
Error	8	2.32		
C. Total	9			
PARAMETER ESTIMATES				
Term	**Estimate**	**Standard Error**	**t Ratio**	**Prob>|t|**
Intercept	13.77	6.67	2.06	0.0729
Latitude	0.49	0.26	1.88	0.0971

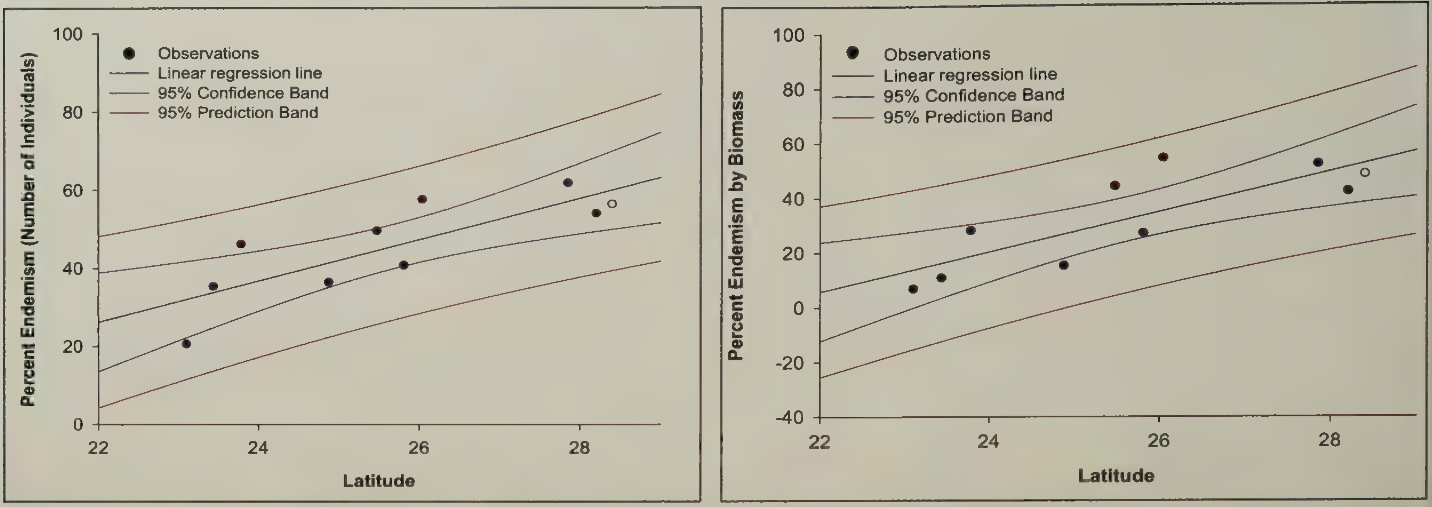


Figure 5.6. Least squares linear regression model for percent endemism by numerical abundance versus latitude (left). Least squares linear regression model for percent endemism by biomass versus latitude (right). Source: DeMartini and Friedlander, 2004.

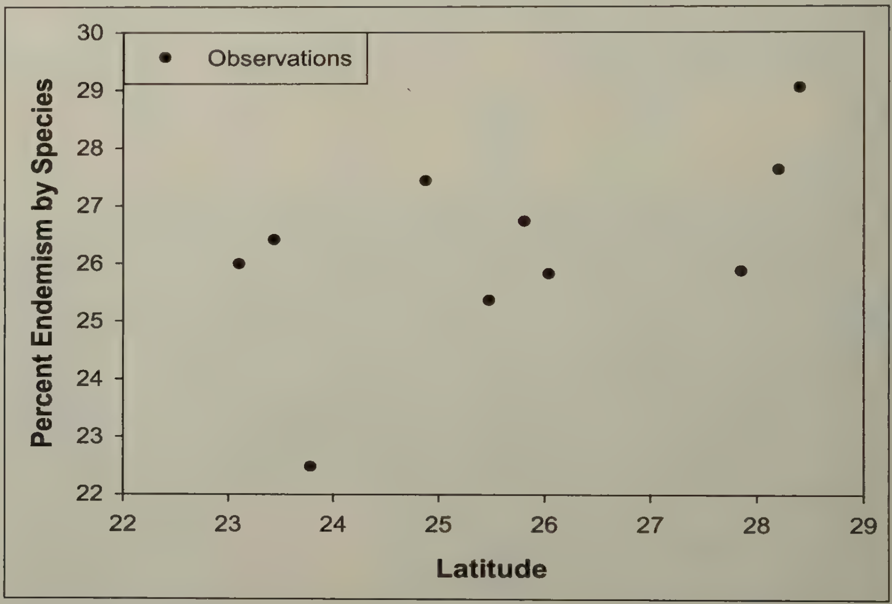


Figure 5.7. Least squares linear regression model for percent endemism by species versus latitude. Source: DeMartini and Friedlander, 2004

LATITUDINAL AFFINITIES AMONG FISHES

Biogeographic forces may promote disparate abundance patterns among some species at opposite ends of the archipelago owing to differences in temperature and other environmental factors. Some species might have a temperate or subtropical bias, whereas others might be better suited to more tropical conditions. To identify latitudinal gradients of abundance, numerical densities as a function of latitude was examined within the NWHI using Spearman rank correlation. Positive correlations indicated a temperate affinity, while negative correlations indicated a tropical affinity. The percentage of individuals with either temperate/subtropical or temperate affinities is an indication of the total fish assemblage affinity at each reef (Table 5.6; Figure 5.8).

Thirty species showed a significant positive correlation (Spearman Rank Correlation, $p<0.05$) with latitude based on numerical density from quantitative fish surveys conducted between 2000 and 2002 (Table 5.7). Of these, 17 (57%) were endemics. Wrasses (Labridae) had the greatest number of species (eight) showing higher latitude affinity followed by damselfishes (Pomacentridae) with four species. Several other species such as knifejaws (*Oplegnathus* spp.) and boarfish (*Evistias acutirostris*) were more abundant at higher latitudes but their low numbers during surveys made the results inconclusive statistically.

Table 5.6. Percentage of numerical abundance at each reef that consisted of species that showed either a temperate/subtropical (northerly) affinity or tropical (southerly) affinity in abundance. Source: Friedlander et al., in prep.

REEF	TEMPERATE/SUBTROPICAL AFFINITY	TROPICAL AFFINITY
NIH	12.97%	16.35%
MMM	28.01%	28.44%
FFS	27.45%	8.57%
GAR	24.52%	14.15%
MAR	51.94%	4.27%
LAY	44.91%	10.24%
LIS	52.90%	3.22%
PHR	52.34%	1.99%
MID	56.08%	0.93%
KUR	63.43%	1.24%

Island/atoll abbreviations used throughout this chapter: NIH = Nihoa Island; MMM = Mokumanamana, FFS = French Frigate Shoals; GAR = Gardner Pinnacles; MAR = Maro Reef; LAY = Laysan Island; LIS = Lisianski Island; PHR = Pearl and Hermes; MID = Midway Atoll; KUR = Kure Atoll

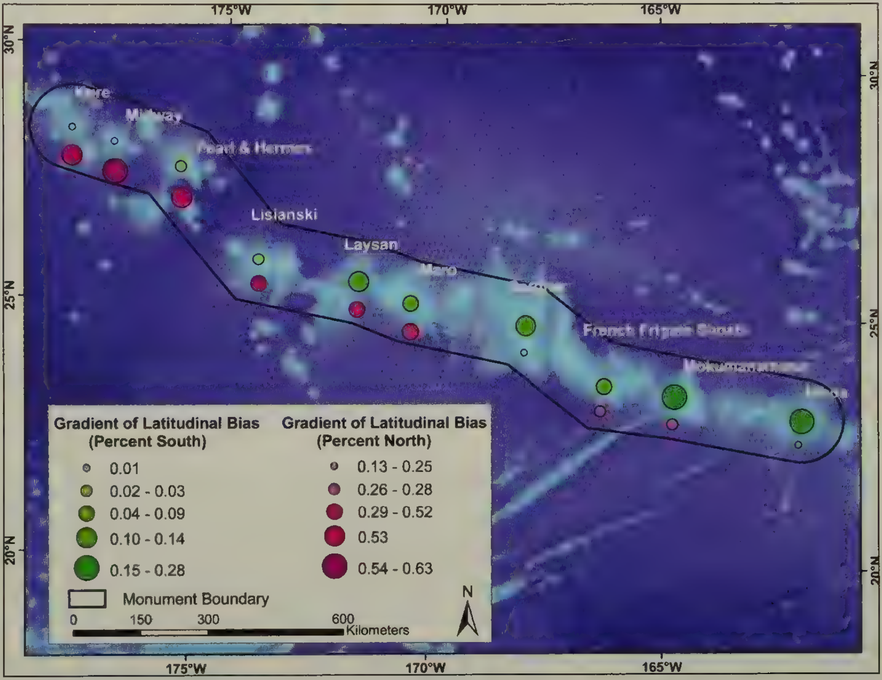


Figure 5.8. Percentage of total numerical abundance (numbers m^{-2}) for species showing a significant latitude gradient of distribution. Source: Friedlander et al., in prep.

Table 5.7. Species with temperate/subtropical affinity (positive correlation with latitude). Endemics in bold. Source: Friedlander et al., in prep.

FAMILY	TAXON NAME	COMMON NAME	HAWAIIAN NAME
Synodontidae	*Synodus ulae*	Ulae Lizardfish	ulae
Holocentridae	***Sargocentron xantherythrum***	**Hawaiian Squirrelfish**	**alaihi**
Scorpaenidae	***Pterois sphex***	**Hawaiian Turkeyfish**	
Serranidae	***Epinephelus quernus***	**Hawaiian Grouper**	**hapuu**
Priacanthidae	***Priacanthus meeki***	**Hawaiian Bigeye**	**aweoweo**
Chaetodontidae	*Chaetodon auriga*	Threadfin Butterflyfish	kikakapu
Pomacanthidae	***Genicanthus personatus***	**Masked Angelfish**	
Pomacentridae	***Abudefduf abdominalis***	**Sargent Major**	**mamo**
Pomacentridae	***Chromis hanui***	**Chocolate-dip Chromis**	

Table 5.7 (continued). Species with temperate/subtropical affinity (positive correlation with latitude). Endemics in bold. Source: Friedlander et al., in prep.

FAMILY	TAXON NAME	COMMON NAME	HAWAIIAN NAME
Pomacentridae	***Chromis ovalis***	**Oval Chromis**	
Pomacentridae	*Stegastes fasciolatus*	Pacific Gregory	
Cirrhitidae	*Paracirrhites forsteri*	Blackside Hawkfish	hilu pili koa
Labridae	***Anampses cuvier***	**Pearl Wrasse**	**opule**
Labridae	***Coris flavovittata***	**Yellowstrip coris**	**hilu**
Labridae	*Gomphosus varius*	Bird Wrasse	hinaleaiiwi, akilolo
Labridae	***Labroides phthirophagus***	**Hawaiian Cleaner Wrasse**	
Labridae	***Stethojulis balteata***	**Belted Wrasse**	**omaka**
Labridae	***Thalassoma ballieui***	**Blacktail Wrasse**	
Labridae	***Thalassoma duperrey***	**Saddle Wrasse**	**hinalea lauwili**
Labridae	*Thalassoma purpureum*	Surge Wrasse	hou
Scaridae	***Calotomus zonarchus***	**Yellowbar Parrotfish**	
Scaridae	***Chlorurus perspicillatus***	**Spectacled Parrotfish**	**uhu uliuli**
Scaridae	***Scarus dubius***	**Regal Parrotfish**	**lauia**
Cheilodactylidae	*Cheilodactylus vittatus*	Hawaiian Morwong	
Acanthuridae	*Acanthurus nigroris*	Bluelined Surgeonfish	maiko
Acanthuridae	*Zebrasoma veliferum*	Sailfin tang	maneoneo
Gobiidae	*Coryphopterus sp.*	Goby	oopu
Gobiidae	*Gnatholepis anjerensis*	Eyebar goby	
Balistidae	*Xanthichthys mento*	Crosshatch Triggerfish	
Diodontidae	*Diodon holocanthus*	Spiny Puffer	oopu okala

Over 63% of the total numerical abundance of fishes at Kure Atoll was composed of species with a high latitude correlation (Figure 5.8). The percentage of high latitude affinity individuals was also substantial at Midway Atoll (56%), Pearl and Hermes Atoll (52%) and Lisianski Island-Neva Shoals (53%). The major break occurs between Maro Reef and Gardner Pinnacle where the numerical abundance of high latitude affinity species dropping from 52% to 25% between these two locations. The lowest percentage of high latitude affinity individuals was observed at Nihoa Island (13%). There was a relatively large shift towards more high latitude affinity individuals between Nihoa and Mokumanamana (28%).

Twenty-one species were significantly and positively correlated ($p<0.05$) with low latitudes based on numerical density estimated on surveys conducted between 2000-2002 (Table 5.8). Only two of these species (9%) were endemics in contrast to the species with high latitude bias, where 54% were found to be endemic. Based on total numerical abundance, the highest percentage of low latitude species was observed at Mokumanamana

Table 5.8 Species with tropical affinity (negative correlation with latitude). Endemics in bold. Source: Friedlander et al., in prep.

FAMILY	TAXON NAME	COMMON NAME	HAWAIIAN NAME
Carcharhinidae	*Carcharhinus amblyrhynchos*	Gray Reef Shark	mano
Carcharhinidae	*Triaenodon obesus*	Whitetip Reef Shark	mano lalakea
Lutjanidae	*Aphareus furca*	Smalltooth Jobfish	wahanui
Lethrinidae	*Monotaxis grandoculis*	Bigeye Emperor	mu
Mullidae	*Parupeneus bifasciatus*	Doublebar Goatfish	munu
Mullidae	*Parupeneus multifasciatus*	Manybar Goatfish	moano
Chaetodontidae	***Chaetodon multicinctus***	**Multiband Butterflyfish**	**kikakapu**
Chaetodontidae	*Chaetodon quadrimaculatus*	Fourspot Butterflyfish	lau hau
Pomacentridae	*Plectroglyphidodon imparipennis*	Brighteye Damselfish	
Cirrhitidae	*Paracirrhites arcatus*	Arc-eye Hawkfish	pili koa
Scaridae	*Calotomus carolinus*	Stareye Parrotfish	
Acanthuridae	*Acanthurus blochii*	Ringtail Surgeonfish	pualu

Table 5.8 (continued). Species with tropical affinity (negative correlation with latitude). Endemics in bold. Source: Friedlander et al., in prep.

FAMILY	TAXON NAME	COMMON NAME	HAWAIIAN NAME
Acanthuridae	*Acanthurus nigrofuscus*	Brown Surgeonfish	maiii
Acanthuridae	*Acanthurus olivaceus*	Orangeband Surgeonfish	naenae
Acanthuridae	*Naso lituratus*	Orangespine Unicornfish	umaumalei
Monacanthidae	***Cantherhines sandwichiensis***	**Squaretail Filefish**	**oili lepa**
Balistidae	*Melichthys niger*	Black Durgon	humuhumuelele
Monacanthidae	*Pervagor aspricaudus*	Lacefin Filefish	
Balistidae	*Rhinecanthus rectangulus*	Reef Triggerfish	humuhumunukunukuapuaa
Balistidae	*Sufflamen bursa*	Lei Triggerfish	humuhumulei
Tetraodontidae	*Canthigaster amboinensis*	Ambon Toby	

(28%) and Nihoa (14%; Figure 5.8). Less than 1% of the number density of fishes counted at Midway consisted of species with a low latitude preference. Similarly, Kure Atoll (1.2%) Pearl and Hermes Atoll (2.0%) and Lisianski Island-Neva Shoals (3.2%) had low numbers of more tropical affinity individuals.

There is a strong positive linear relationship between the percentage of individuals with temperate/subtropical affinities and latitude (Table 5.9, Figure 5.9), while there is a strong negative linear relationship with the percentage of individuals with tropical affinities and latitude (Table 5.10, Figure 5.9). A major faunal break occurred around Maro and Laysan, where the numerical abundance of northern and southern affinity species were more similar. Although species with northern affinities were still more abundant than species with southern affinities south of Maro, the overall numerical abundance of these northern species averaged 23% south of Maro, but 54% to the north. Species with tropical affinities account for 17% of fish numbers south of Maro, but only 4% to the north.

Table 5.9. Least squares linear regression model for species exhibiting temperate/subtropical affinity and latitude. Source: Friedlander et al., in prep.

ANALYSIS OF VARIANCE				
Source	**DF**	**Mean Square**	**F Ratio**	**Prob > F**
Model	1	0.20	33.57	0.0004
Error	8	0.01		
C. Total	9			
PARAMETER ESTIMATES				
Term	**Estimate**	**Standard Error**	**t Ratio**	**Prob>|t|**
Intercept	-1.57	0.34	-4.57	0.0018
Latitude	0.08	0.01	5.79	0.0004

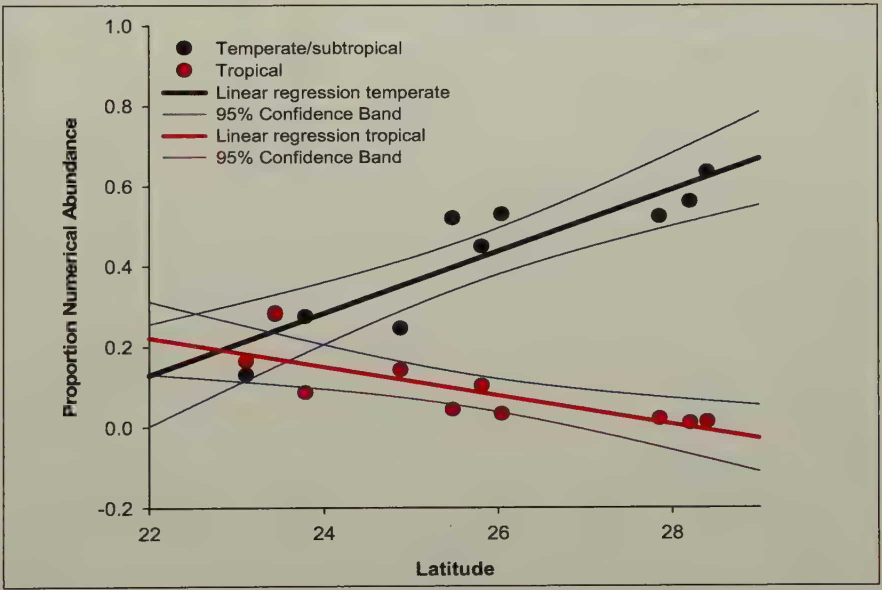


Figure 5.9. Relationship between latitude and numerical abundance of species with temperate/subtropical and tropical affinities. Results of least squares linear regression. Temperate/subtropical = -1.56 + 0.07*Latitude, Tropical = 1.00 - 0.03*Latitude. Source: Friedlander et al., in prep.

Fish Recruitment

The planktonic dispersal of reef fishes is an important process linked to the persistence of benthic reef populations. Recruitment of reef fishes increased with latitude, and was especially pronounced at the four northernmost reefs that had a larger proportion of YOY recruits (DeMartini and Friedlander, 2004). During 2000-2002, recruit fish densities were generally greater upchain to the northwest (versus downchain) and a larger number of endemic (versus non-endemic) species recruited to a greater extent upchain in the NWHI (Figure 5.10; DeMartini and Friedlander, 2004). YOY recruit length frequencies did not differ for most species between northern and southern reefs, suggesting that a seasonal lag in spawning and recruitment at higher latitudes cannot explain the greater YOY densities observed there. Disproportionate recruitment at higher-latitude reefs may be related to higher levels of within-reef and regional reseeding at higher latitudes. This was first indicated by survey data collected during the 1990s at French Frigate Shoals and Midway (DeMartini et al., 2002; DeMartini, 2004). During this period, there was consistently higher recruitment of YOY life stages of fishes at Midway Atoll versus French Frigate Shoals despite the generally greater densities of older-stage fishes at French Frigate Shoals (Figure 5.11).

Table 5.10. Least squares linear regression model for species with tropical affinity and latitude. Source: NWHI RAMP, unpub. data.

ANALYSIS OF VARIANCE				
Source	**DF**	**Mean Square**	**F Ratio**	**Prob > F**
Model	1	0.04	14.17	0.0055
Error	8	0.01		
C. Total	9			
PARAMETER ESTIMATES				
Term	**Esti-mate**	**Standard Error**	**t Ratio**	**Prob>|t|**
Intercept	1.01	0.24	4.12	0.0033
Latitude	-0.04	0.01	-3.76	0.0055

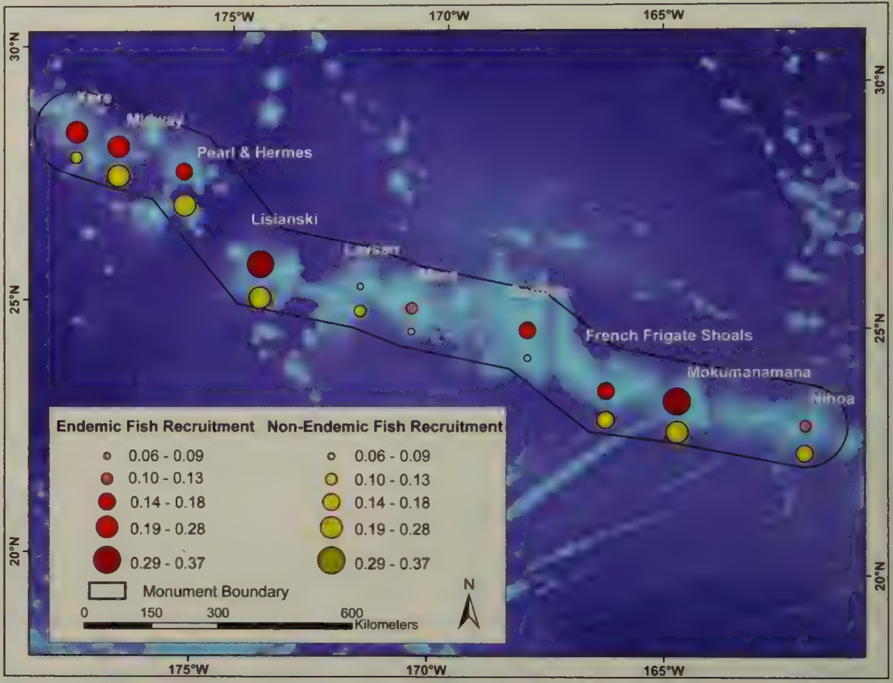


Figure 5.10. Geographic patterns of the Recruit Index (ratio of YOY sized to larger individuals) for all pooled major species of endemic and non-endemic reef fishes. Source: DeMartini and Friedlander, 2004; map: L. Wedding.

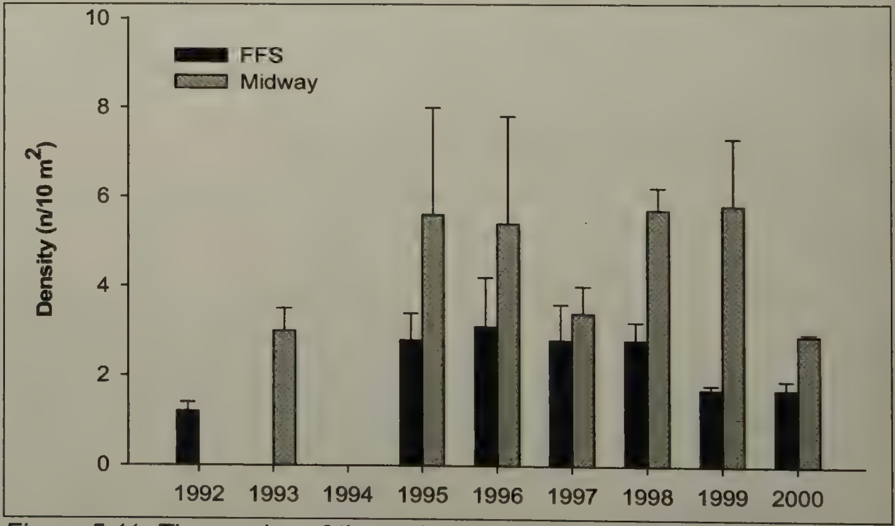


Figure 5.11. Time series of the estimated mean numerical density of YOY of all taxa at French Frigate Shoals and Midway during each survey year. Each vertical bar represents one southeast of the estimated survey year grand mean for both major habitats. Source: DeMartini, 2004.

GENERAL FISH ASSEMBLAGE STRUCTURE

Dominance by species was revealed by plotting relative percent contribution by each species to total biomass at each reef. A limited number of species accounted for the majority of the biomass for most locations. Giant trevally (ulua, *Caranx ignobilis*) was the dominant species by weight at Lisianski (50% of total biomass), Pearl and Hermes (43%), Laysan (32%) and Maro (30%; Figure 5.12). Chub (nenue, *Kyphosus* spp.) is the most dominant taxa by weight at Nihoa and accounts for 35% of the biomass.

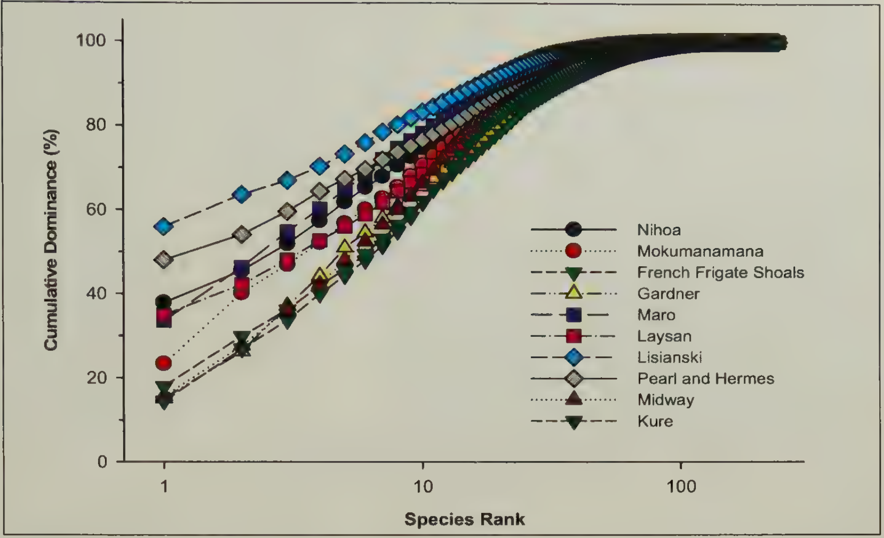


Figure 5.12. Ordinary dominance curve for each reef based on biomass. Source: NWHI RAMP, unpub. data.

The similarity of fish assemblages among reefs in the NWHI was compared based on biomass density for each species at each reef (Figures 5.13, 5.14). Two atolls (Kure and Midway) had high concordance and formed a distinct cluster relative to all other islands. The two basalt islands (Nihoa and Mokumanamana) were also distinct in their fish assemblages while Gardner Pinnacles, the other basalt rock, was unique in its fish assemblage based on biomass. Pearl and Hermes and Lisianski were the most similar based on fish assemblage biomass but also cluster at lower levels with Maro, Laysan, and to a lesser extent, French Frigate Shoals.

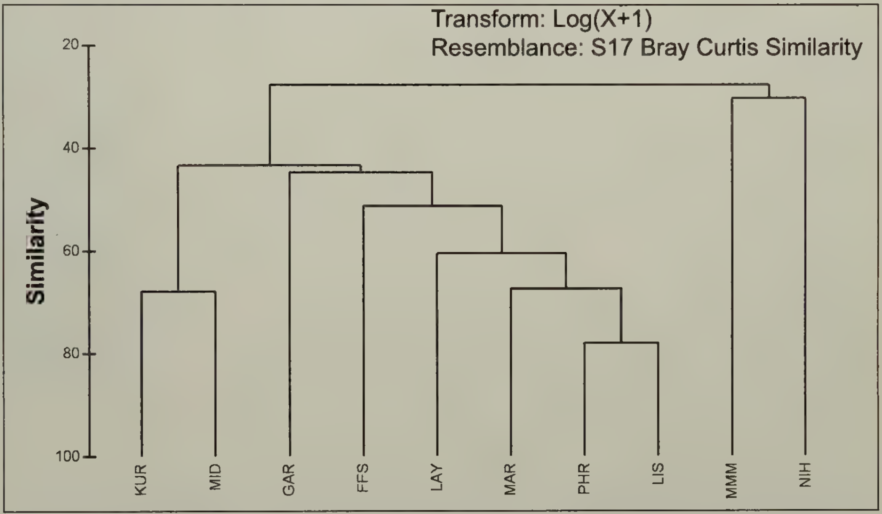


Figure 5.13. Bray Curtis similarity dendrogram showing similarities among reef based on biomass. Source: NWHI RAMP, unpub. data.

Similarity based on numerical abundance showed two distinct clusters with Nihoa being an extreme outlier (Figures 5.15, 5.16). Midway and Pearl and Hermes exhibited similar assemblage structure, as did French Frigate Shoals with Maro, and Kure with Lisianski. Mokumanamana, Gardner, and to a lesser extent, Laysan, exhibited similar assemblage structure but were less correlated than those in the other cluster. Nihoa was unique in its assemblage structure based on numerical abundance.

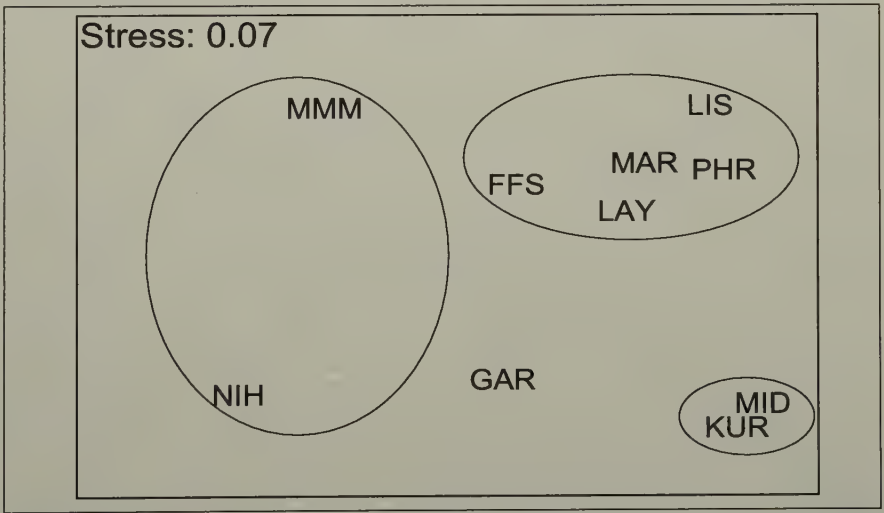


Figure 5.14. Nonmetric multi-dimensional scaling plot of reef similarities derived from biomass abundance of species. Similarities based on Bray-Curtis Similarity Index. Biomass abundance ln(x+1) transformed. Source: NWHI RAMP, unpub. data.

Trophic Structure

Overall, apex predators accounted for 47% of total fish biomass, followed by herbivores (31%) and secondary consumers (22%). Pearl and Hermes had the highest percentage of apex predators (67%), with French Frigate Shoals (61%) and Lisianski-Neva Shoal (58%) also having substantial apex predator biomass (Figure 5.17). More than 65% of the apex predator biomass observed within the NWHI consisted of giant trevally.

Apex predator biomass increases up the chain reaching a maximum at Pearl and Hermes Atoll before declining dramatically at Midway and Kure atolls (Figure 5.17; DeMartini and Friedlander, 2004). The extremely low biomass of apex predators at Midway and Kure has been attributed to previous extractive fishing activities at both locations as well as a tag-and-release recreational sport fishery at Midway (DeMartini et al., 2002; DeMartini et al., 2005).

Herbivores were dominant in terms of biomass at Nihoa (56%) and Midway (56%). Chubs accounted for most of the herbivore biomass at Nihoa while the endemic spectacled parrotfish (*Chlorurus perspicillatus*) was most predominant at Midway and Kure. The lowest total biomass was recorded at Mokumanamana (0.45 t ha^{-1}) while Pearl and Hermes had the lowest percentage of herbivores (11%). Secondary consumer biomass ranged from a high at Midway (0.91 t ha^{-1}) and Pearl and Hermes (0.89 t ha^{-1}) to a low at Mokumanamana (0.26 t ha^{-1}). The saddle wrasse was the dominant species among secondary consumers at both Midway and Pearl and Hermes.

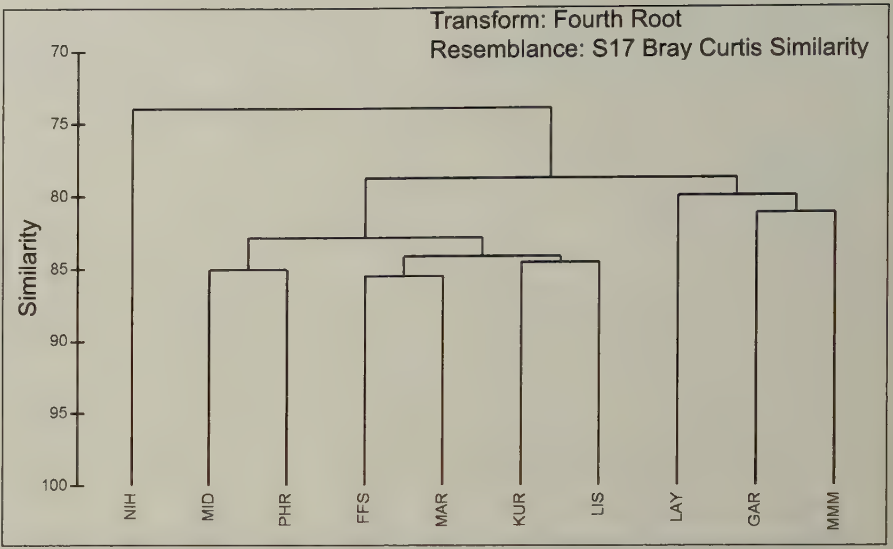


Figure 5.15. Bray Curtis similarity dendrogram showing similarities among reef based on numerical abundance. Source: NWHI RAMP, unpub. data.

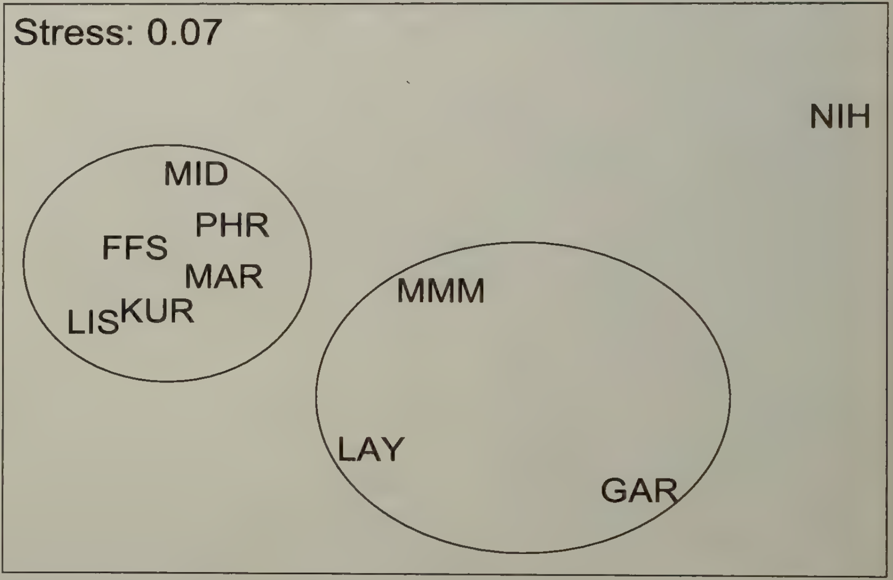


Figure 5.16. Nonmetric multi-dimensional scaling plot of reef similarities derived from numerical abundance of species. Similarities based on Bray-Curtis Similarity Index. Numerical abundance fourth root transformed. Source: NWHI RAMP, unpub. data.

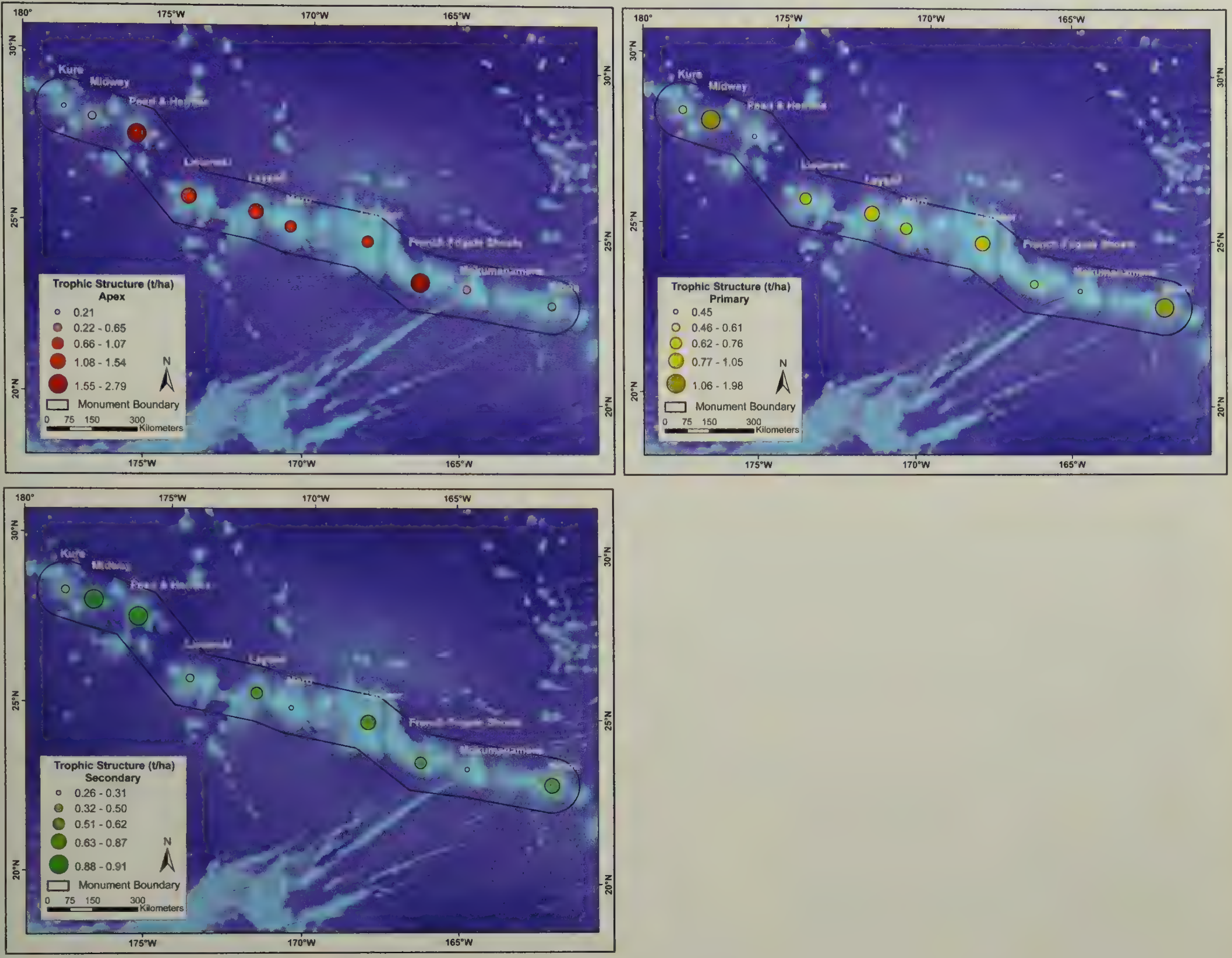


Figure 5.17. Percent biomass by consumer groups at each reef. Bubbles are proportional to total biomass (t ha^{-1}). Source: NWHI RAMP, unpub. data.

Biomass Size Spectra

Biomass densities of pooled taxa were evaluated as size spectra relative to standardized length classes; our analysis revealed that there were relatively more and greater numbers of large individual fish at Pearl and Hermes and French Frigate Shoals than elsewhere in the NWHI (Figure 5.18). Overall, biomass based on the intercept of the biomass-to-body size relation (i.e. abundance at the midpoint of the length distribution) was lowest at Kure, Mokumanamana and Nihoa (Figure 5.19).

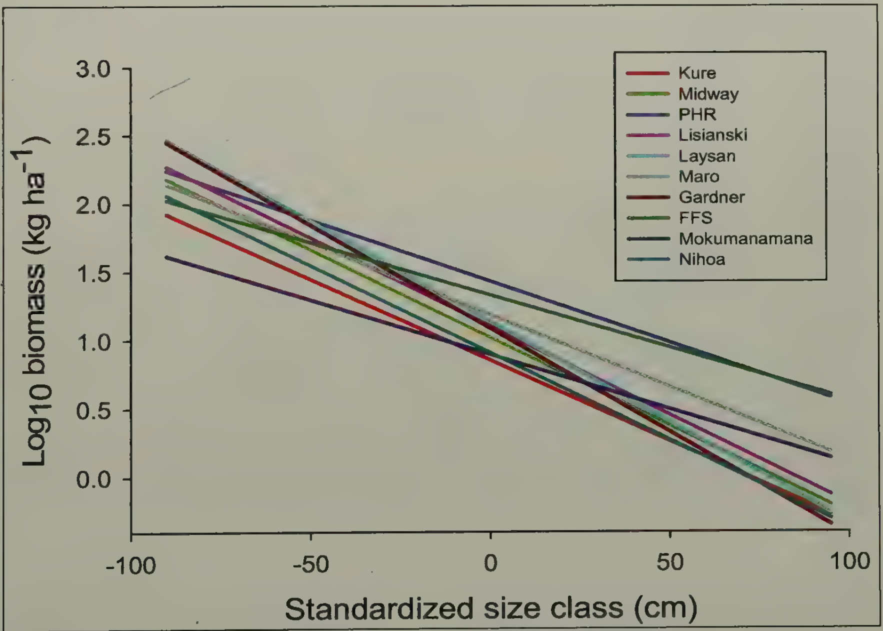


Figure 5.18. Biomass size spectra for all fishes greater than 15 cm at each of the major reefs in the NWHI. Source: NWHI RAMP, unpub. data.

Shark Distribution Patterns

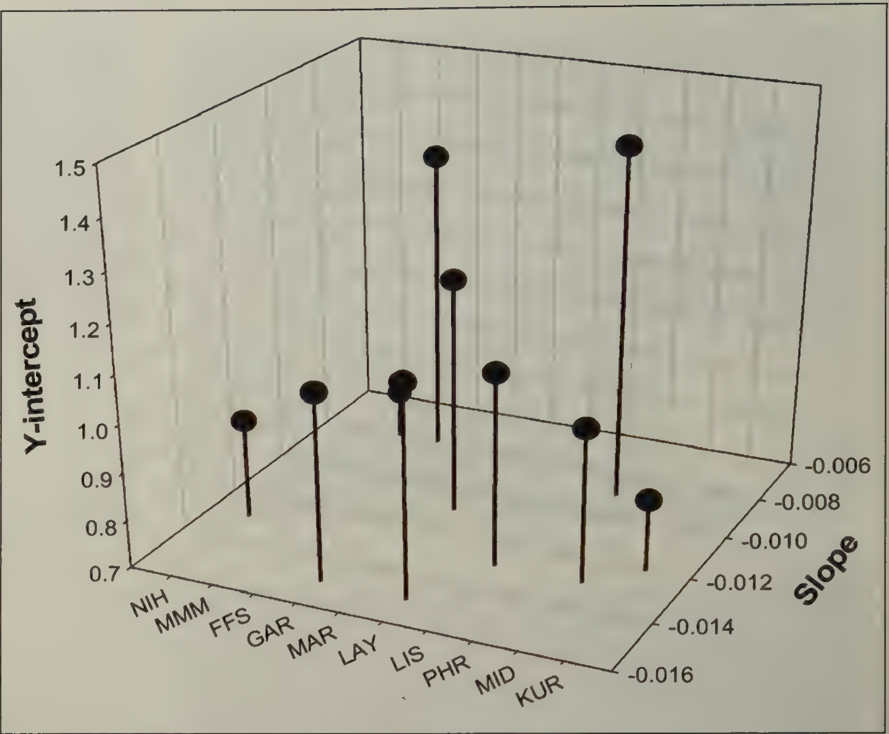


Figure 5.19. Plot of slope and y-intercept from size spectra regressions. Source: NWHI RAMP, unpub. data.

Sharks are an important component of the reef fish assemblage in the NWHI accounting for 28% of apex predator biomass and 13% of total reef fish biomass on the fore reef. Grey reef (*Carcharhinus amblyrhynchos*, 8.4%), Galapagos (*Carcharhinus galapagensis*, 10.2%; Figure 5.20) and whitetip reef sharks (*Triaenodon obesus*, 8.6%; Figure 5.20) comprised similar percentages of total apex predator biomass while blacktip reef sharks (*Carcharhinus melanopterus*) were much less abundant than the other three species and comprised only 0.3% of total biomass and 0.6% of apex predator biomass in the fore reef habitats. The biogeographic distribution patterns of gray reefs and Galapagos sharks were markedly different within the NWHI (Figure 5.21). Gray reef sharks were replaced by Galapagos sharks moving northward along the NWHI chain. Galapagos sharks are less abundant at Nihoa, Mokumanamana, and French Frigate Shoals but are very abundant northwest of Gardner Pinnacles. Gray reefs become less abundant northward. Papastamatiou et al. (2006) examined data from the Hawaii Shark Control Program between 1967 and 1980 and found Galapagos and tiger sharks (*Galeocerdo cuvier*) to be more abundant in the NWHI compared to the MHI, while sandbar sharks (*Carcharhinus plumbeus*) were more common in the MHI compared with the NWHI. These data showed gray reef sharks were more numerous in the NWHI compared with the MHI. Within the NWHI, this species was more abundant at Mokumanamana and French Frigate Shoals at the lower end of the NWHI and less abundant at the northern reefs of Maro and Midway. Interspecific competition, owing to dietary overlap, perhaps influences the distribution of these sharks throughout the Hawaiian Islands (Papastamatiou et al., 2006).

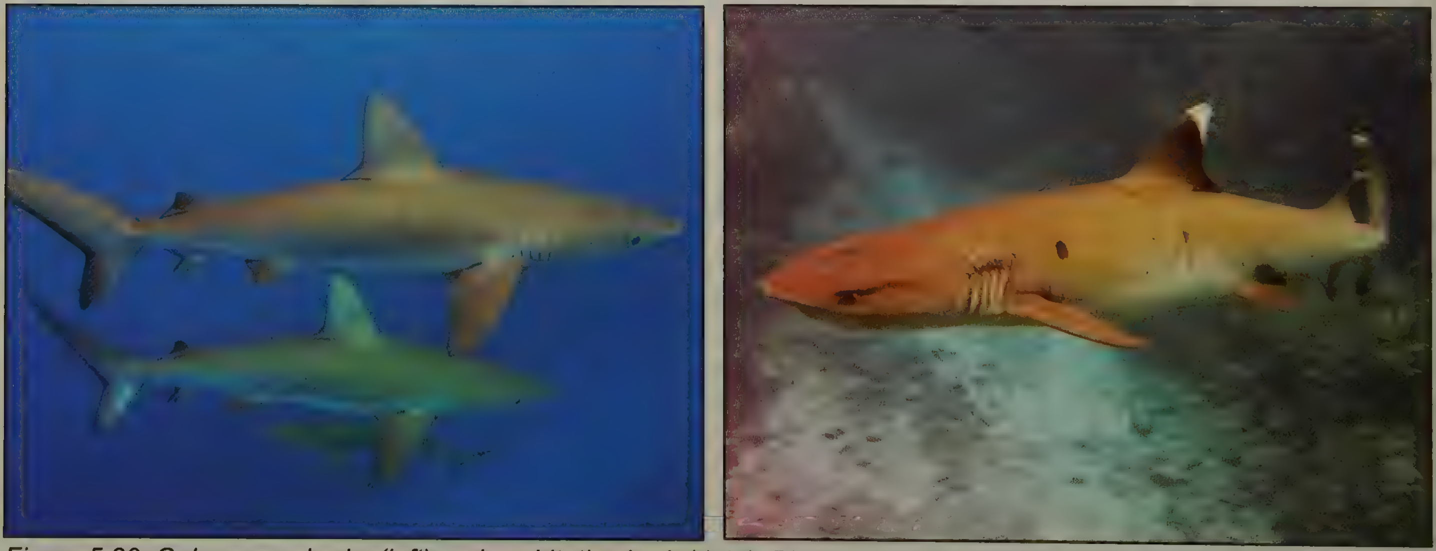


Figure 5.20. Galapagos sharks (left) and a whitetip shark (right). Photos: J. Maragos and A. Friedlander.

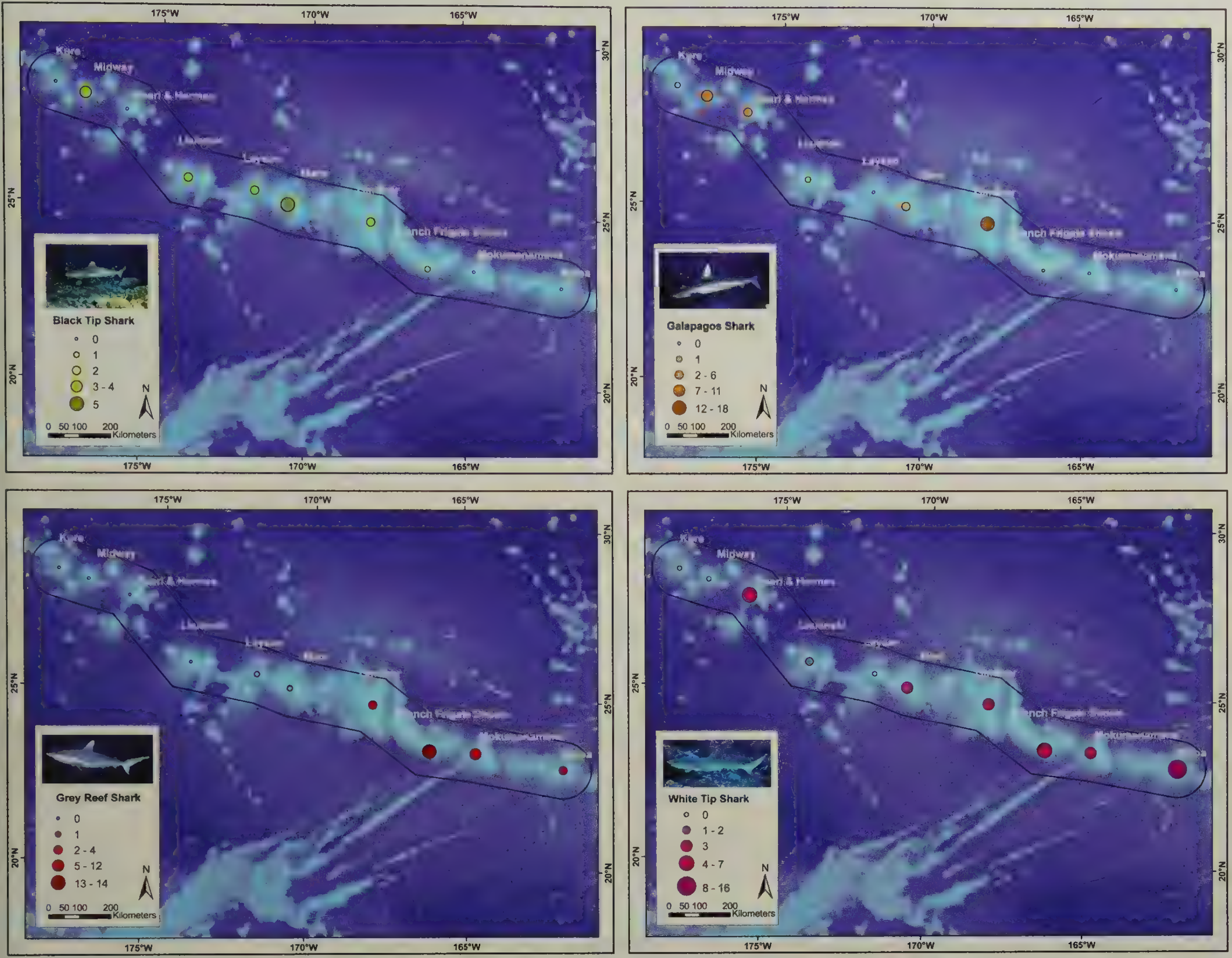


Figure 5.21. Biogeographic distribution of sharks in the NWHI based on number of individuals ha^{-1}. Values are numbers ha^{-1} and are for fore reef habitats only. Source: NWHI RAMP, unpub. data.

Influence of Influence of Predators on Prey Fishes

The effects of apex predation, primarily by giant trevally, are pervasive. Apex predators structure prey population sizes and age distributions and strongly influence the reproductive and growth dynamics of other harvested species (such as parrotfish) as well as smaller-bodied, lower-trophic-level fishes on shallow NWHI reefs (DeMartini and Friedlander, 2006). Perhaps the strongest evidence for the controlling influence of apex predation on the structure of fish assemblages in the NWHI is provided by data on the size, composition and spatial distribution of prey species (Figure 5.22; DeMartini et al., 2005).

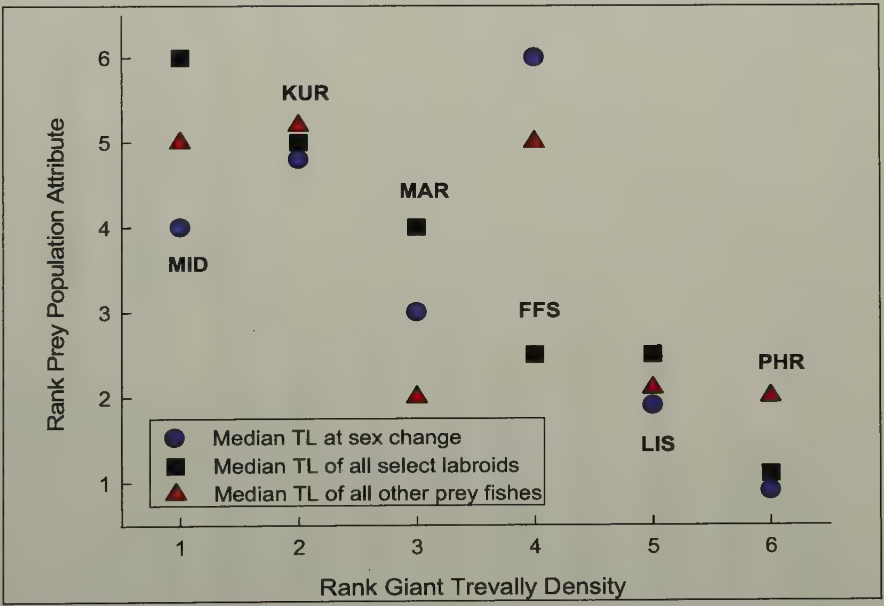


Figure 5.22. Scatterplot of the ranks of prey population attributes (median body length at sex change in the four major labroid species, median body lengths of all eight select species of labroids, and median body length of all other prey fishes) versus the ranks of giant trevally densities. Source: Demartini et al., 2005.

DeMartini (2004) documented the habitat-specific spatial distributions of juvenile and other small-bodied fishes particularly susceptible to predation and recognized the importance of back reef, lagoon patch reef and other sheltered (wave-protected) habitats as nursery areas for juvenile reef fishes (Figure 5.23). This study, based on re-analyses of data collected at French Frigate Shoals and Midway Atoll during the 1990s, has contributed substantially to development of both "essential fish habitat" and "habitat areas of particular concern" concepts in recognizing the greater per-unit-area value of atolls due to their larger proportion of sheltered juvenile nursery habitats (DeMartini, 2004).

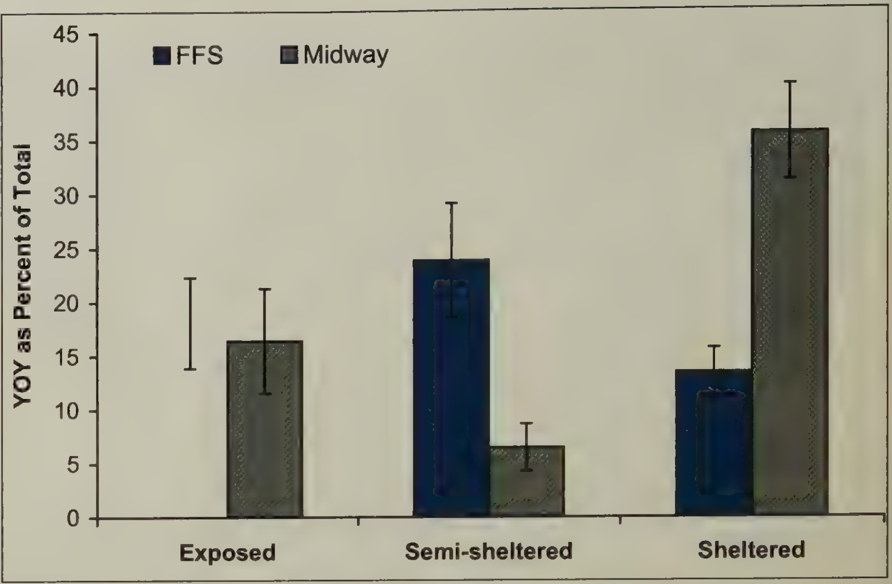


Figure 5.23. Percentage contribution of YOY to overall YOY plus older-stage densities. Source: adapted from DeMartini, 2004.

Updated Comparison of Fish Assemblage Metrics Among NWHI Reefs

Based on data collected from initial surveys in 2000, 2001, 2002 and new sites surveyed in 2007, fish assemblage characteristics were compared among all reefs. Fish species richness appeared highest at Nihoa, Gardner and Laysan and lowest at Mokumanamana, Maro and Kure but these differences were not significant (Table 5.11, Figure 5.24). The number of individual fishes observed on transects differed significantly different among reefs (Table 5.12, Figure 5.25,). Midway, followed by Pearl and Hermes had the highest number of individuals while Mokumanamana and Maro had the lowest. Biomass also differed significantly different among reefs (Table 5.13, Figure 5.26; $F_{9,409} = 3.64$, $p < 0.001$) with the highest biomass at Gardner, Nihoa and Pearl and Hermes. The lowest fish biomass was recorded at Kure and Mokumanamana.

Table 5.11. Fish species richness Analysis of Variance among reefs. Source: NWHI RAMP, unpub. data.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO	PROB > F
Reef	9	686.699	76.3	1.64	0.1005
Error	400	18548.44	46.37		
C. Total	409	19235.14			

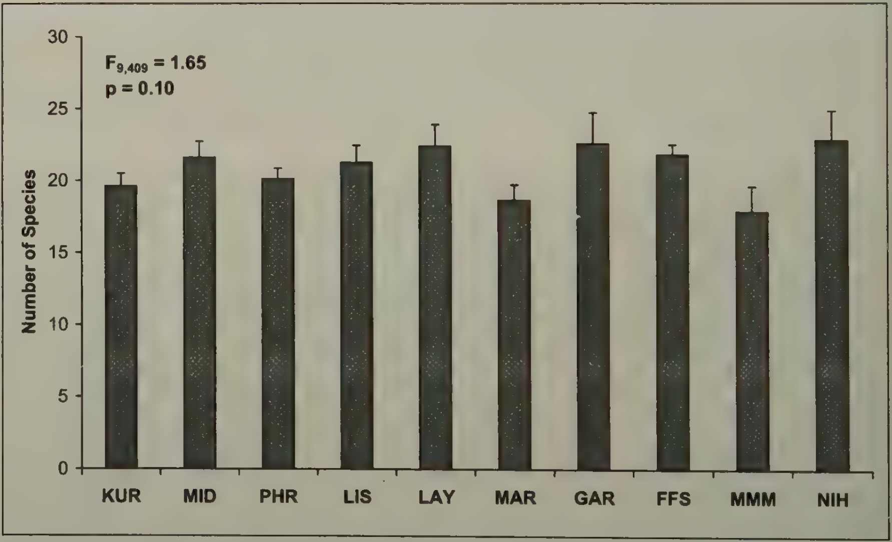


Figure 5.24. Mean species richness per transect from REA data from 2000-2002 and 2007. Error bars are standard error of the mean. Source: NWHI RAMP, unpub. data.

Table 5.12. Fish biomass in t ha^{-1} (ln[x+1]) Analysis of Variance among reefs. Comparisons for all pairs using Tukey-Kramer HSD. Levels not connected by same letter are significantly different. Source: NWHI RAMP.

ANALYSIS OF VARIANCE					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob > F**
Reef	9	6.78	0.75	6.18	<.0001
Error	400	48.80	0.12		
C. Total	409	55.58			
Level	**Multiple Comparisons**	**Mean**			
Midway	A	1.20			
PHR	AB	0.99			
Lisianski	BC	0.87			
FFS	BC	0.86			
Gardner	ABC	0.83			
Kure	BC	0.83			
Laysan	BC	0.83			
Nihoa	BC	0.81			
Maro	BC	0.79			
MMM	C	0.58			

Table 5.13. Fish biomass in t ha^{-1} (ln[x+1]) Analysis of Variance among reefs. Comparisons for all pairs using Tukey-Kramer HSD. Levels not connected by same letter are significantly different. Source: NWHI RAMP.

ANALYSIS OF VARIANCE					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob > F**
Reef	9	9.30	1.03	3.64	0.0002
Error	400	113.64	0.28		
C. Total	409	122.93			
Level	**Multiple Comparisons**	**Mean**			
Gardner	AB	1.26			
Lisianski	A	1.14			
Laysan	AB	1.13			
Midway	A	1.12			
Nihoa	AB	1.11			
PHR	A	1.09			
FFSs	A	1.01			
Maro	AB	0.97			
MMM	AB	0.74			
Kure	B	0.70			

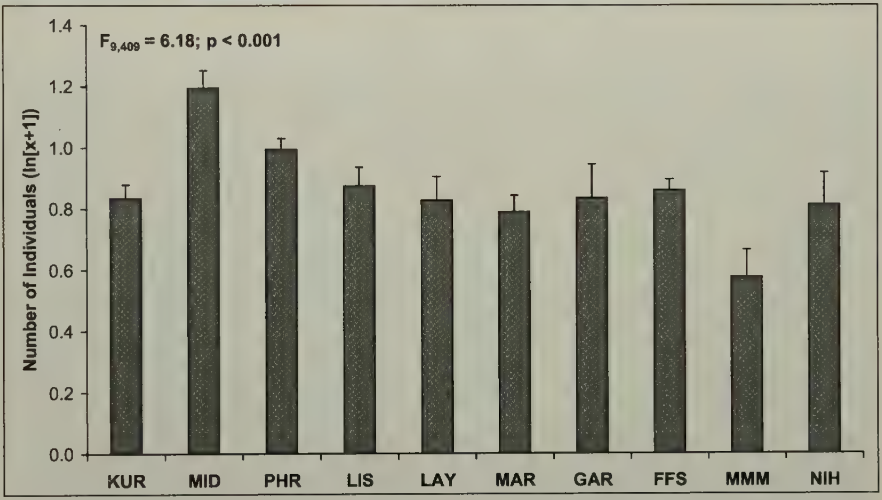


Figure 5.25. Mean number of individuals per transect from REA data from 2000-2002 and 2007. Error bars are standard error of the mean. Source: NWHI RAMP, unpub. data.

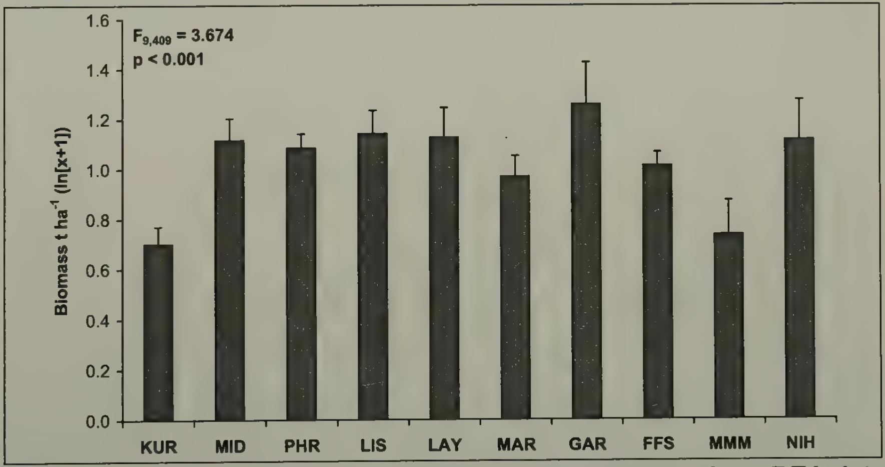


Figure 5.26. Mean biomass in t ha^{-1} (ln[x+1]) per transect from REA data from 2000-2002 and 2007. Error bars are standard error of the mean. Source: NWHI RAMP, unpub. data.

Comparisons of fish assemblage characteristics among reefs in the NWHI revealed Pearl and Hermes Atoll to have the highest average rank among the seven metrics examined (Table 5.14, Figure 5.27). Pearl and Hermes yielded the highest endemism, highest total biomass, and highest apex predator biomass among all reefs. Midway and French Frigate Shoals was second and third highest rank with Midway having the greatest number of individuals and French Frigate Shoals having the highest richness. Lisianski-Neva Shoals had the highest recruit index (ratio of YOY to older sized individuals).

Mokumanamana had the lowest rank integrated over all fish assemblage metrics and had the lowest number of species per transect and the lowest number of individuals per transect. Maro Reef and Kure Atoll also had low values for most fish assemblage metrics. Since all sampling was conducted within the boundaries of each Special Preservation Area (SPA), these rankings by reef should also serve as a ranking by SPA.

Table 5.14. Rank values for fish assemblage metrics among the 10 emergent reefs of the NWHI. Source: NWHI RAMP, unpub. data.

Reef	Endemism	Total Species	# Species	Number Individuals	Total Biomass*	Apex Predator Biomass	Mean Recruitment	Average Rank
Pearl and Hermes	10	9	4	9	10	10	6	8.29
Midway	7	8	6	10	9	3	8	7.29
French Frigate Shoals	5	10	7	7	8	8	5	7.14
Lisianski	9	2	5	8	4	9	10	6.71
Gardner	3	1	9	6	7	6	3	5
Laysan	4	5	8	4	5	7	1	4.86
Kure	8	7	3	5	2	1	7	4.71
Nihoa	1	4	10	3	6	2	4	4.29
Maro	6	6	2	2	3	5	2	3.71
Mokumanamana	2	3	1	1	1	4	9	3

**Total biomass excludes back reef and lagoon habitats to reduce bias and compares habitat types.*

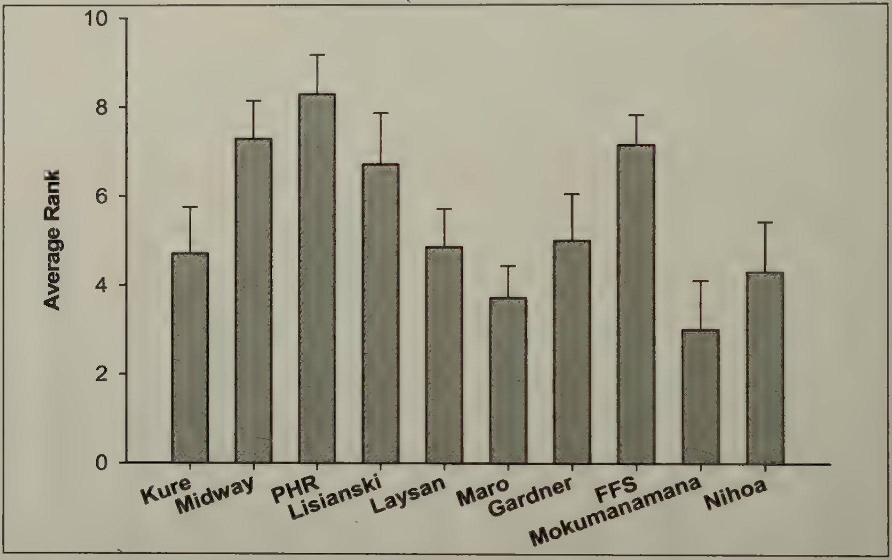


Figure 5.27. Mean rank values for fish assemblage metrics among the 10 emergent reefs of the NWHI. Source: NWHI RAMP, unpub. data.

Comparisons with the MHI

The most conspicuous biological patterns observed in the NWHI was the strikingly higher numerical and biomass densities and greater average body sizes of reef fishes in the NWHI compared to the MHI, particularly for large jacks, reef sharks and other apex predators (Figure 5.28). Also notable is the overall reduced numbers and biomass density of lower trophic level fishes in the MHI, including lower-level carnivores. Differences in fish biomass density between the MHI and NWHI represent both the severe depletion of apex predators from fishing and the heavy exploitation of other species, primarily lower trophic-level carnivores on shallow reefs of the MHI (Friedlander and DeMartini, 2002). Fish densities at less exploited sites (such as uninhabited Kahoolawe and no-take areas) within the MHI further reinforce the conclusions that these differences are caused by fishing. Recent comparisons of fish biomass and size structure among accessible sites and inaccessible sites near versus distant from population centers in the MHI further indicate that depressed MHI stocks are primarily the result of fishing rather than other anthropogenic stressors such as poorer habitat quality (Williams et al., 2008). Were it not for extraction, reef fish productivity in the MHI should be higher (not lower) than in the NWHI as a result of greater terrigenous nutrient input and more diverse juvenile nursery habitats at the vegetated, high windward islands. Other anthropogenic stressors insufficiently explain the lower densities of reef fishes in the MHI (Friedlander and DeMartini, 2002; Friedlander and Brown, 2004). The differences in fish assemblage structure provide evidence of the high level of exploitation in the MHI. Further, the sharp contrast between the two areas in terms of fish density and composition provides a valuable perspective for developing ecosystem-level management of reef systems in the MHI and the NWHI (Friedlander and DeMartini, 2002).

Catalogue of the NWHI Fish Assemblages

We conclude this chapter with a characterization of the fish assemblages at each of the 10 NWHI reefs, ordered from from Nihoa Island to Kure Atoll. The assemblages at each reef are described in terms of three basic metrics (species richness and numerical and biomass densities), with the latter two metrics examined for dominant species.

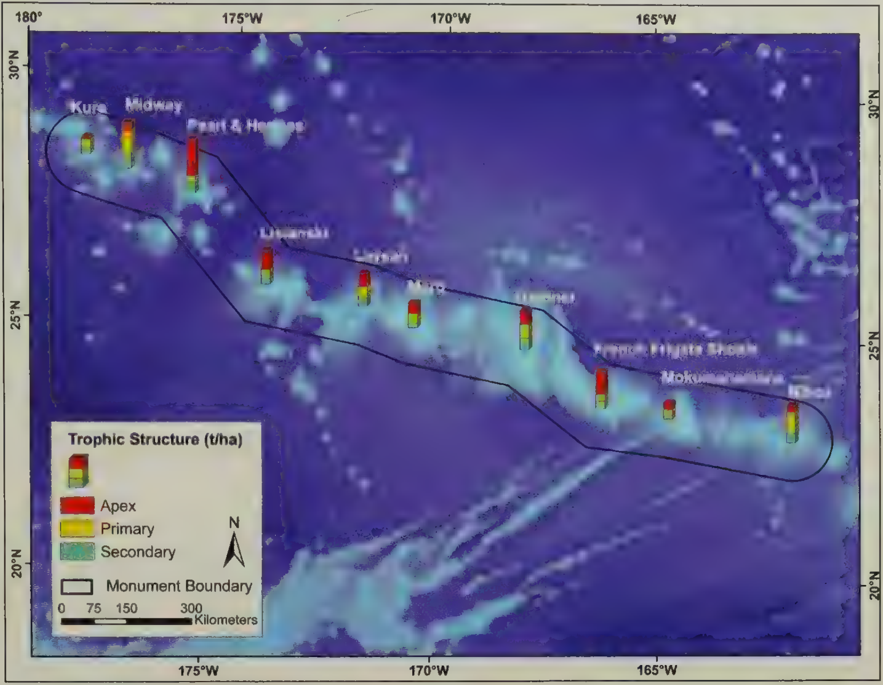


Figure 5.28. Comparisons of total biomass and biomass among consumer groups between the NWHI and MHI. Source: Friedlander and DeMartini, 2002.

Nihoa Island

Despite its small size (Figure 5.29), Nihoa Island ranked first overall in fish species richness per transect among all reefs surveyed in the NWHI. This is in contrast to the total species richness, which ranked amongst the lowest in the NWHI. High species richness is related to the proximity to MHI and our observation of the highest percentage of species with a tropical-biased distribution. Species richness ranged from to 36.6 to 8.6 ($\bar{x}$ =22.8, SD ± 11.02; Table 5.15, Figure 5.30).

Numerical abundance of fishes ranked eighth overall and ranged from 5.32 to 0.14 individuals m^{-2} ($\bar{x}$ =1.61, SD ± 1.57; Table 5.15, Figure 5.30). The blackfin chromis (*Chromis vanderbilti*), a planktivorous damselfish, comprised 35% of the total numerical density, followed by chubs (16%), and the brown surgeonfish (*Acanthurus nigrofuscus*, 6%). The highest species richness, biomass, and numerical abundance were observed off the leeward side of the island where high complexity basalt benches provided good quality habitat for a diversity of species of various sizes.

Biomass ranked fifth overall. Mean biomass per station was 2.88 t ha^{-1} (SD ± 3.37) and ranged from a high of 12.03 to a low of 0.39. Chubs accounted for 43% of the total biomass at Nihoa Island, followed by whitetip reef sharks (7%), the introduced blueline snapper (*Lutjanus kasmira*, 7%) and black durgons (*Melichthys niger*, 5.5%).

Figure 5.29. Aerial image of Nihoa Island. Photo: J. Maragos.

Table 5.15. Fish assemblage characteristics for Nihoa Island. Source: NWHI RAMP, unpub. data

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	11	22.8	11.02	3.32	15.4	30.21
Number of Individuals (m^2)	11	1.61	1.57	0.47	0.55	2.66
Biomass (t ha^{-1})	11	2.88	3.37	1.01	0.62	5.14

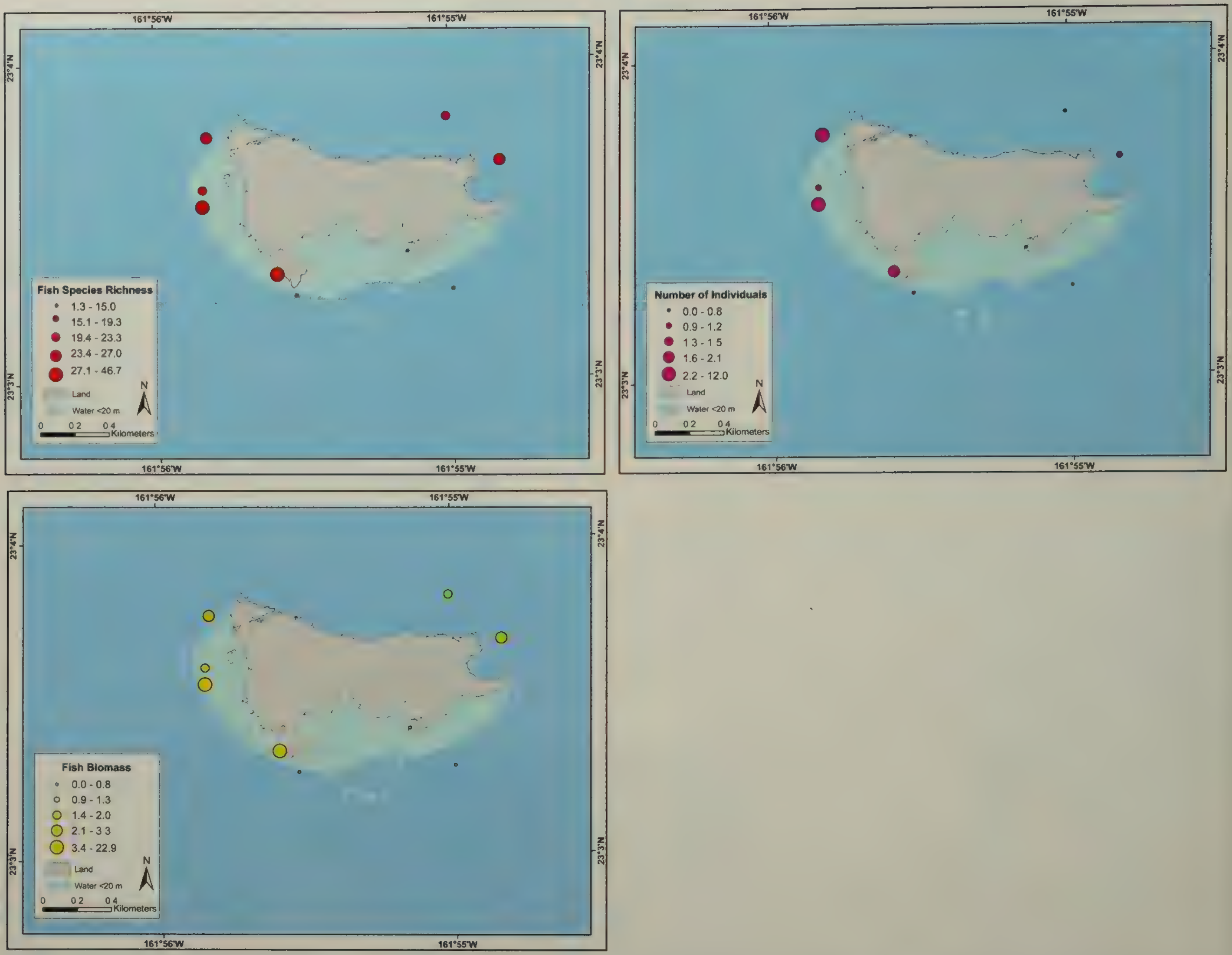


Figure 5.30. Fish assemblage characteristics for Nihoa Island. Species richness (top left), number of individuals (top right), and biomass (t ha^{-1}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Mokumanamana

Mokumanamana yielded the lowest species richness per transect ($\bar{x}$ =17.8, SD ± 4.45) among all reefs (Table 5.16, Figure 5.31, SD ± 4.45). Higher species richness was observed on the northwestern portion of the island.

Table 5.16. Fish assemblage characteristics for Mokumanamana Island. Source: NWHI RAMP, unpub. data.

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	15	17.82	4.45	1.15	15.36	20.29
Number of Individuals (m^2)	15	0.81	0.35	0.09	0.61	1
Biomass (t ha^{-1})	15	1.25	1.06	0.27	0.67	1.84

Mokumanamana also had the lowest numerical density of fishes observed among reefs in the NWHI (0.81 individuals/m^2, SD±0.35) and ranged from 1.49 to 0.43. The planktivorous blackfin chromis accounted for 19% of total numerical density, followed by the saddle wrasse (*Thalassoma duperrey*,18%) and the orangeband surgeonfish (*Acanthurus olivaceus*, 10%). The low overall values for fish assemblage characteristics at Mokumanamana are likely the result of low habitat complexity where the majority of stations having extremely low relief. For example, Shark Bay, located on the northern portion of the island, exhibited substrate of flat planed surfaces as a result of scouring by surge and sediment suspension.

Fish biomass also ranked lowest at Mokumanamana. The distribution of biomass was extremely variable (CV = 0.85) but was highest off the points on the north and eastern parts of the island. Biomass ranged from 4.11 to 0.36 t ha^{-1} with a grand mean of 1.25 (SD ± 1.06). Apex predators accounted for 43% of the total biomass

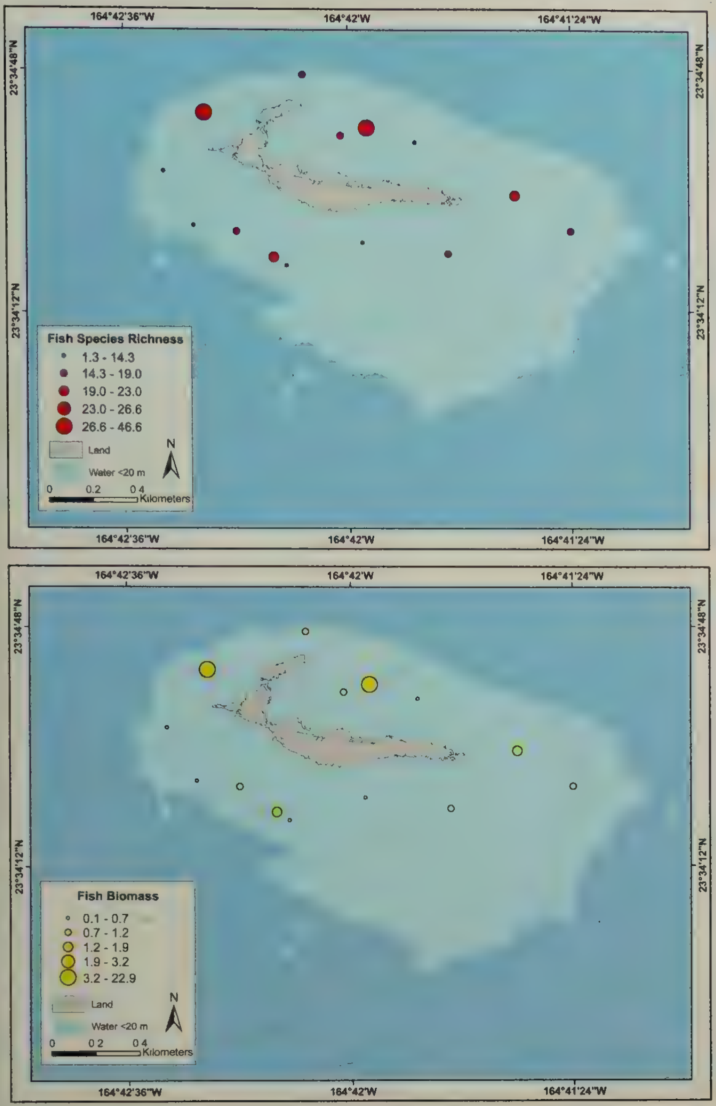


Figure 5.31. Fish assemblage characteristics for Mokumanamana. Species richness (top left), number of individuals (top right), and biomass (t ha^{-1}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

and were dominated by grey reef sharks with 25% of total fish biomass. Other important contributors to fish biomass included orangeband surgeonfish (17%), black durgons (17%), giant trevally (6%) and whitetip reef sharks (5%).

French Frigate Shoals Fish

Species richness at French Frigate Shoals averaged 21.8 (SD ± 7.7) and was the forth highest among all reefs surveyed (Table 5.17, Figure 5.32). Fore reef habitats had the highest species richness ($\bar{x}$ = 26.1), followed by back reef ($\bar{x}$ = 20.7), and lagoon habitats ($\bar{x}$ = 19.3). Species richness tended to be higher on the windward fore reef (Table 5.18).

Table 5.17. Fish assemblage characteristics for French Frigate Shoals across all habitat types. Source: NWHI RAMP, unpub. data.

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	93	21.78	7.73	0.8	20.19	23.37
Number of Individuals (m^2)	93	1.69	1.83	0.19	1.31	2.07
Biomass (t ha^{-1})	93	2.28	2.22	0.23	1.83	2.74

Fish density ranged from 12.0 to 0.26 individuals/m^2 and averaged 1.69 (SD ± 1.8). Numerical abundance was highest in lagoon habitat (1.77 individuals/m^2) and was dominated by the domino damselfish (*Dascyllus albisella*, 9%), saddle wrasse (8%) and goldring surgeonfish (*Ctenochaetus strigosus*, 7%). Density was low-

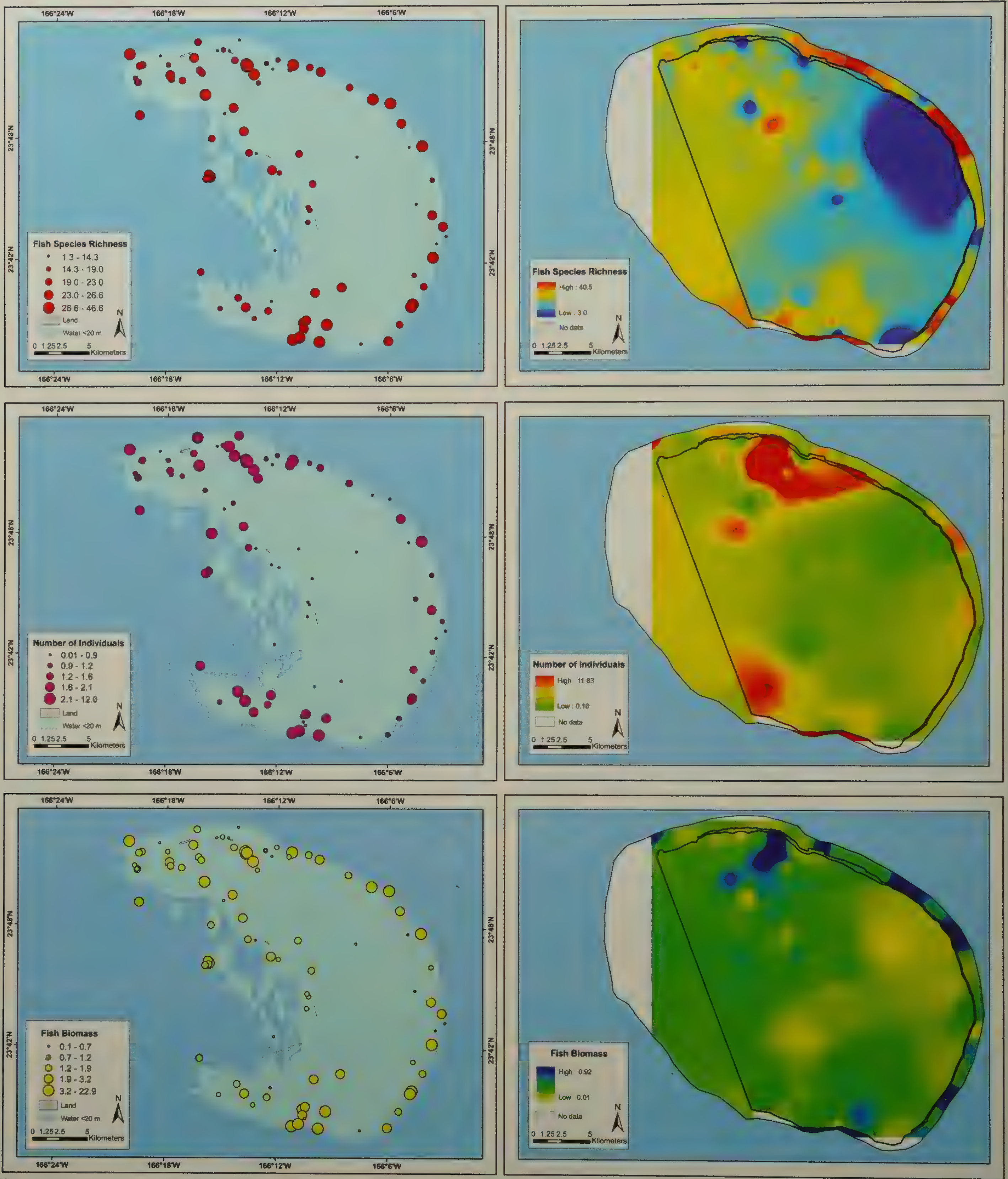


Figure 5.32. Fish assemblage characteristics for French Frigate Shoals: species richness (top row), number of individuals (middle row), and biomass (t ha^{-1}, bottom row). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

est on the fore reef ($\bar{x}$ = 1.55 m^2), where the blackfin chromis and saddle wrasse each accounted for 10% of the total number of individuals. Numerical abundance on the back reef habitat ($\bar{x}$ = 1.55) was composed of the saddle wrasse (12%), the introduced blueline snapper (9%) and blackfin chromis (8%). The greatest number of individuals was observed at stations near Tern Island at the northern portion of the atoll and at the southern pass near Disappearing Island.

Table 5.18. Fish assemblage characteristics for French Frigate Shoals for each major habitat type. Source: NWHI RAMP, unpub. data.

BACK REEF	**NUMBER**	**MEAN**	**STD DEV**	**STD ERR MEAN**	**LOWER 95%**	**UPPER 95%**
Species	2	20.67	0.47	0.33	16.43	24.9
Number of Individuals (m^2)	2	1.55	0.68	0.48	-4.52	7.61
Biomass (t ha^{-1})	2	0.97	0.1	0.07	0.06	1.87
LAGOON						
Species	58	19.34	6.83	0.9	17.54	21.14
Number of Individuals (m^2)	58	1.77	2.16	0.28	1.2	2.34
Biomass (t ha^{-1})	58	1.87	1.72	0.23	1.42	2.33
FORE REEF						
Species	33	26.13	7.63	1.33	23.43	28.84
Number of Individuals (m^2)	33	1.56	1.12	0.19	1.16	1.96
Biomass (t ha^{-1})	33	3.08	2.8	0.49	2.09	4.08

Fish biomass density (t ha^{-1}) was highest on the fore reef ($\bar{x}$ = 3.08 t ha^{-1}) and was dominated by giant trevally (26%) and grey reef sharks (21%). French Frigate Shoals ranked third in total fore reef biomass among all locations. Species composition by weight in the lagoon ($\bar{x}$ = 1.87) primarily consisted of giant trevally (13%), followed by grey reef sharks (6%), the endemic spectacled parrotfish (6%) and bluespine unicornfish (*Naso unicornis*, 6%). The back reef habitat yielded the lowest biomass ($\bar{x}$ = 0.97) where giant trevally (25%), bluelined snappers (14%) and grey reef sharks (10%) comprised nearly half of the total biomass. Biomass was highest near Tern Island at the northern portion of the atoll and at the southern pass near Disappearing Island.

Gardner Pinnacles

A total of 10 stations were sampled for fishes at Gardner Pinnacles with the sampling effort representing a large portion of the hard bottom habitat less than 18.2 m in depth including windward and leeward exposures. Mean species richness was 22.5 (SD ± 6.5) with a range from 36 to 13.3 species per transect. Gardner ranked second in mean species richness even though total species richness was low (Table 5.19 and Figure 5.33).

Table 5.19. Fish assemblage characteristics for Gardner Pinnacles across all habitat types. Source: NWHI RAMP, unpub. data.

LEVEL	**NUMBER**	**MEAN**	**STD DEV**	**STD ERR MEAN**	**LOWER 95%**	**UPPER 95%**
Species	10	22.55	6.48	2.05	17.91	27.19
Number of Individuals (m^2)	10	1.39	0.72	0.23	0.88	1.91
Biomass (t ha^{-1})	10	2.99	2.11	0.67	1.48	4.5

Despite its small size, the biomass density of fishes at Gardner Pinnacles ranked fourth overall. Fish biomass ranged from 7.68 to 0. 29 t ha-1 ($\bar{x}$ = 2.99, SD ± 2.11; Table 5.19, Figure 5.33). Chubs dominated by weight, comprising 17% of the total fish biomass. This species was followed by bluefin trevally (*Caranx melampygus*, 11%) and grey reef sharks (10%). Highest biomass was observed off the northwest basalt pinnacle where large boulders formed a highly complex habitat with a vertical wall down to the reef pavement at 18.2 m. This station was dominated by bluefin (25%) and giant trevally (13%).

Fish density ranged from 2.88 to 0.62 individuals/m^2 ($\bar{x}$ = 1.39, SD ± 0.73). Chubs accounted for 16% of total numerical abundance, followed by saddle wrasse (9%), and oval chromis (*Chromis ovalis*, 7%). The drop-off at the northwest sea stack harbored a large number of planktivores including oval chromis and milletseed butterflyfish (*Chaetodon miliaris*). These two species comprised 32% of the numerical density of fishes at this station.

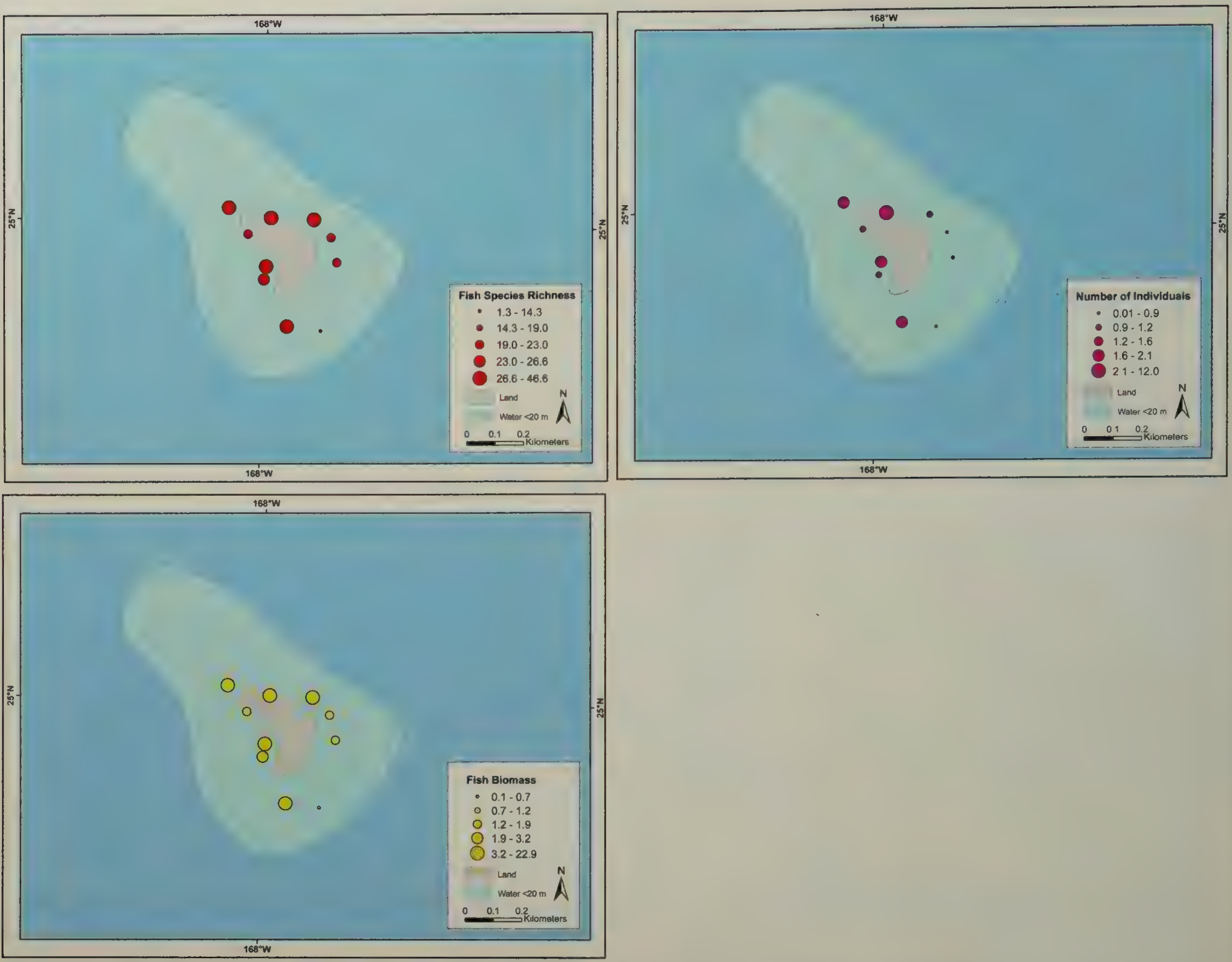


Figure 5.33. Fish assemblage characteristics for Gardner Pinnacles. Species richness (top left), number of individuals (top right), and biomass (t ha^{-1}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Maro Reef

Maro Reef was second only to Mokumanamana Island in having the lowest mean species richness observed on quantitative surveys (Table 5.20, Figure 5.34). Mean species richness was 18.6 (SD ± 4.6) and ranged from 27.67 to 12.56 per station. Relatively high species numbers were recorded at stations along the westernmost, leeward reef sections.

Table 5.20. Fish assemblage characteristics for Maro Reef across all habitat types. Source: NWHI RAMP, unpub. data.

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	42	18.65	4.58	0.71	17.22	20.08
Number of Individuals (m^2)	42	1.26	0.51	0.08	1.1	1.42
Biomass (t ha^{-1})	42	1.92	1.7	0.26	1.39	2.46

The number of individual fish observed on transects at Maro was also low compared with other reefs in the NWHI ($\bar{x}$ = 1.3, SD ± 0.5). Small resident species such as saddle wrasse (16%), Pacific Gregory (*Stegastes fasciolatus*, 13%) and juvenile parrotfishes (11%) comprised much of the numerical density observed at Maro. Several stations on the windward, northeast side of the reef possessed higher numbers of individuals compared to other stations and were dominated by small juvenile parrotfishes.

Biomass also was low compared to most other locations and ranked second lowest after Mokumanamana Island. Biomass density ranged from 6.12 to 0.41 t m^{-2} ($\bar{x}$ = 1.9, SD ± 1.7); and similar to the observed richness

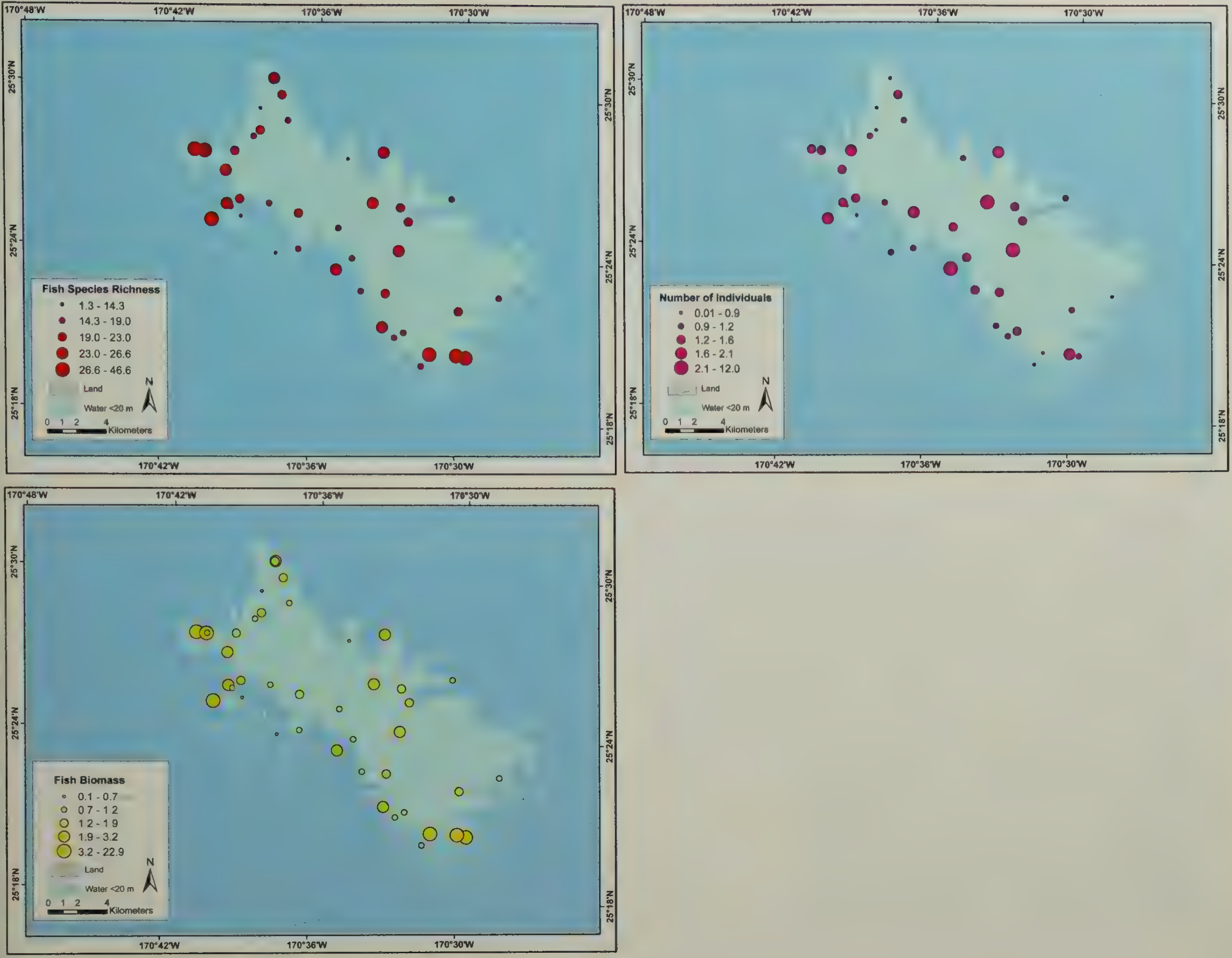


Figure 5.34. Fish assemblage characteristics for Maro Reef. Species richness (top left), number of individuals (top right), and biomass (t ha^{-1}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

patterns, relatively high biomass was observed along the westernmost, leeward reef sections. More than 25% of the biomass at Maro Reef consisted of giant trevally, followed by spectacled parrotfish (11%), Galapagos sharks (7%), bullethead parrotfish (*Chlorurus sordidus*, 6%) and whitetip reef sharks (6%).

Laysan Island Fish

Laysan Island ranked third in mean species richness ($\bar{x}$ = 22.4, SD ± 5.2; Table 5.21, Figure 5.35), ranging from 32.7 to 13.3. The highest species richness occurred on the windward fore reef, off the northeast corner of the island.

Table 5.21. Fish assemblage characteristics for Laysan Island across all habitat types. Source: NWHI RAMP, unpub. data.

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	20	22.37	5.19	1.16	19.94	24.79
Number of Individuals (m^2)	20	1.34	0.53	0.12	1.1	1.59
Biomass (t ha^{-1})	20	2.55	2.09	0.47	1.58	3.53

Numerical abundance ranged from 2.46 to 0.42 individuals m^{-2} ($\bar{x}$ = 1.3, SD ± 0.5) and was dominated by saddle wrasses (18%), followed by convict tangs (*Acanthurus triostegus*, 11%), and Pacific Gregory (7%), respectively. No strong spatial patterns to numerical abundance were observed among the sampling stations at Laysan.

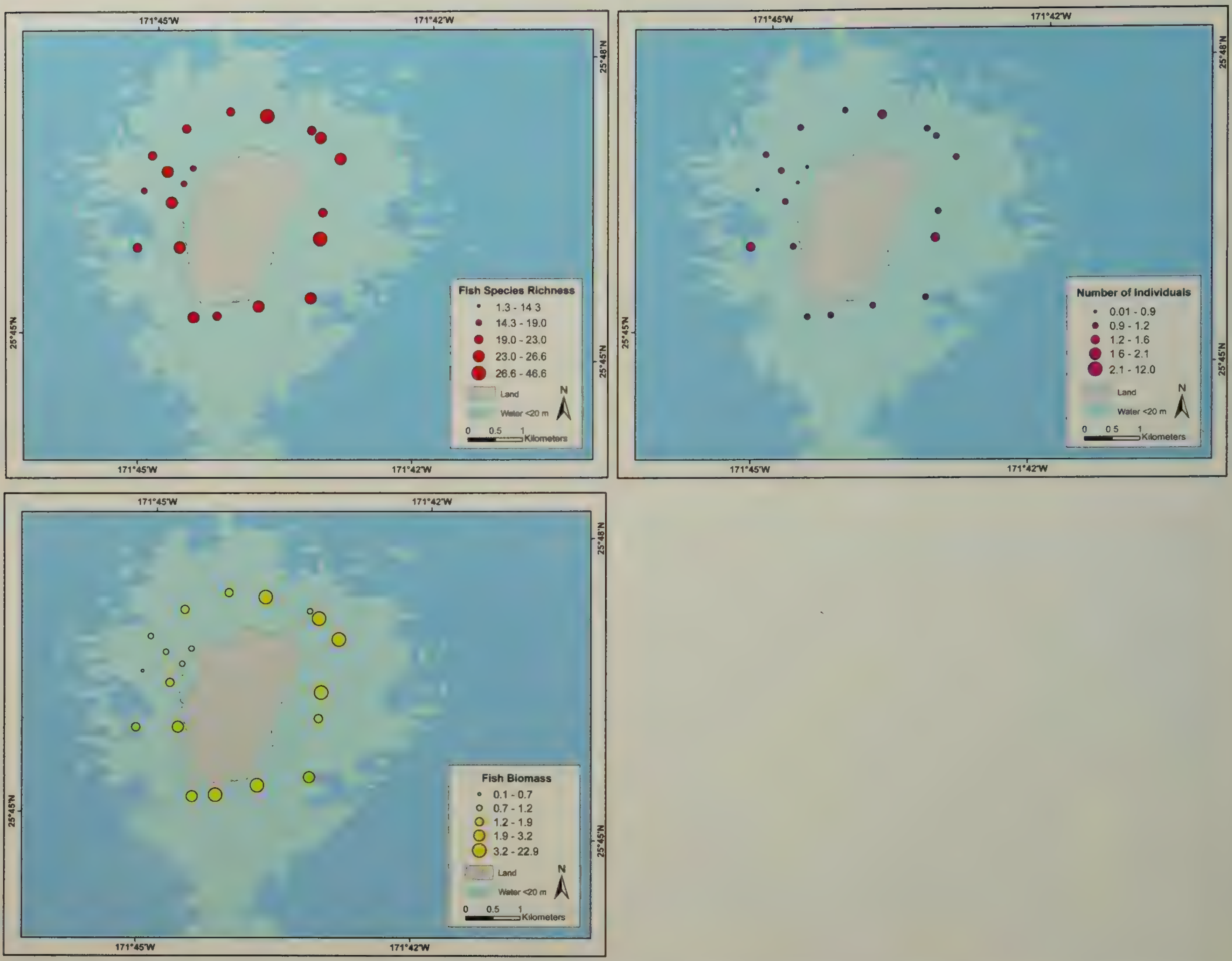


Figure 5.35. Fish assemblage characteristics for Laysan Island. Species richness (top left), number of individuals (top right), and biomass (t ha^{-1}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Laysan Island ranked sixth in mean biomass ($\bar{x}$ = 2.5, SD ± 2.1), ranging from 5.15 to 0.85 t ha^{-1}. The windward, northeast fore reef harbored the highest biomass. Giant trevally comprised 37% of total biomass, followed by whitebar surgeonfish (*Acanthurus leucopareius*, 6%) and the endemic spectacled parrotfish (6%).

Lisianski Island-Neva Shoals

Lisianski Island-Neva Shoals ranked sixth in mean species richness per station ($\bar{x}$ = 21.2, SD ± 4.13) and ranged from 24.7 to 20.7 (Table 5.22, Figure 5.36). The greatest number of species per station was observed on the leeward side (northwest and west) of Lisianski.

Table 5.22. Fish assemblage characteristics for Lisianski Island-Neva Shoals across all habitat types. Source: NWHI RAMP, unpub. data.

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	32	21.23	4.13	0.73	19.75	22.72
Number of Individuals (m^2)	32	1.45	0.53	0.09	1.26	1.64
Biomass (t ha^{-1})	32	2.47	1.71	0.3	1.85	3.08

Numerical abundance at Lisianski Island-Neva Shoals ranked third overall. Mean fish density was 1.45 individuals/m^2 (SD ± 0.5) and ranged from 1.66 to 0.99 individuals/m^2. Dominant species include saddle wrasse (12%), goldring surgeonfish (11%), Pacific Gregory (11%) and juvenile parrotfish (8%). No spatial patterns were observed for fish density across the reef system.

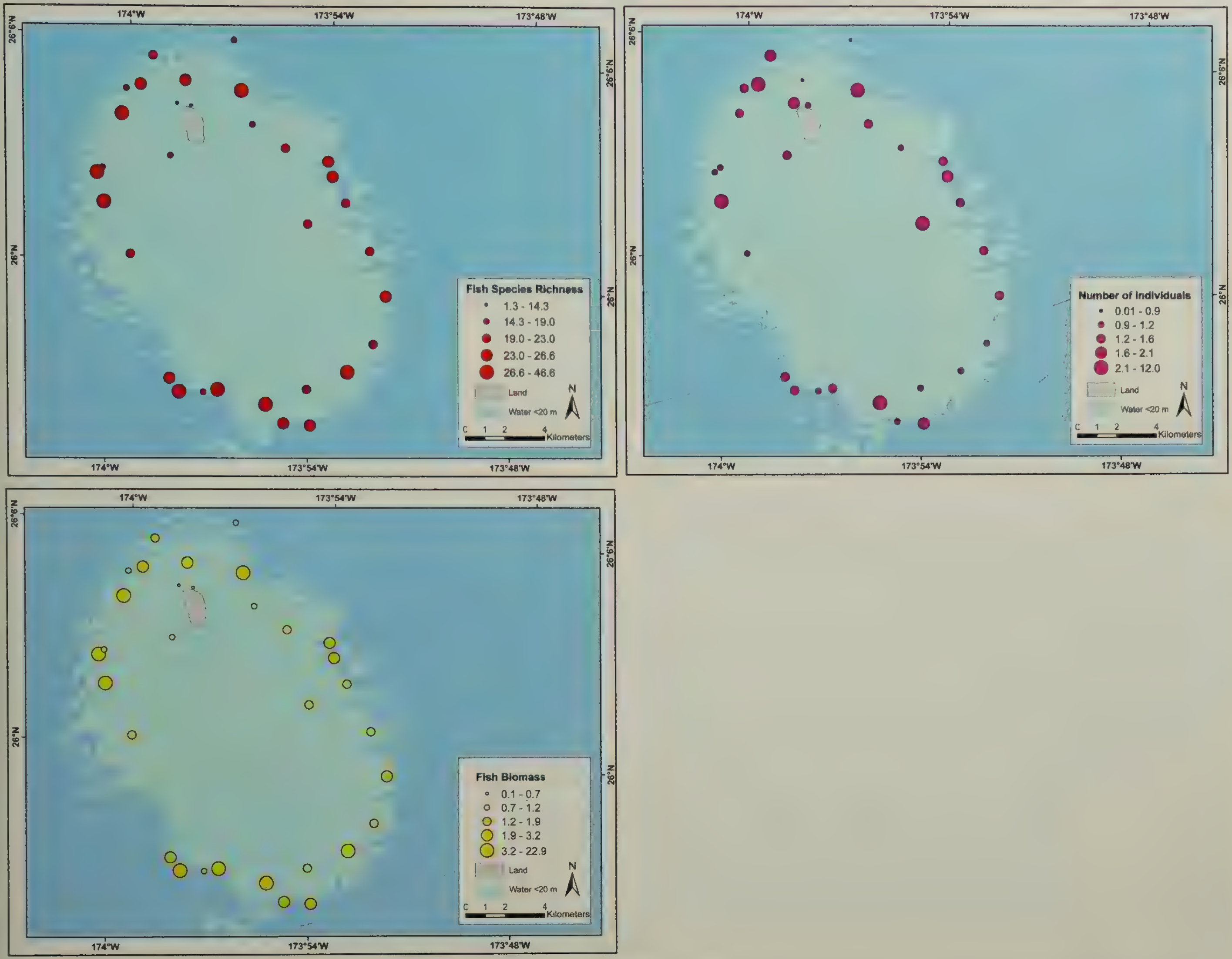


Figure 5.36. Fish assemblage characteristics for Lisianski Island-Neva Shoals. Species richness (top left), number of individuals (top right), and biomass (t ha^{-1}; bottom left). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Lisianski Island-Neva Shoals ranked seventh in mean biomass compared to all other reefs. Mean fish biomass was 2.5 t ha^{-1} (SD ±1.7) and ranged from 5.15 to 0.8. Biomass was highest along the southeast portion of Neva Shoals, in an area of high coral cover and high habitat complexity. Giant trevally accounted for the majority (51%) of the total biomass. This was followed in importance by three species of parrotfishes: the endemic spectacled parrotfish (8%), bullethead parrotfish (4%) and the endemic regal parrotfish (*Scarus dubius*, 4%).

Pearl and Hermes Atoll

Mean species richness at Pearl and Hermes Atoll was 20.1 (SD ± 7.2) and ranked seventh overall (Table 5.23, Figure 5.37). Species richness was significantly higher (F_{291} = 24.49, p<0.001) on the fore reef ($\bar{x}$ = 24.0, SD ± 6.9) compared with the lagoon ($\bar{x}$ = 16.9, SD ± 6.0) and back reef ($\bar{x}$ = 17.0, SD ± 4.6) habitats (Table 5.24).

Table 5.23 Fish assemblage characteristics for Pearl and Hermes Atoll across all habitat types. Source: NWHI RAMP, unpub. data.

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	91	20.12	7.21	0.76	18.62	21.62
Number of Individuals (m^2)	91	1.82	0.83	0.09	1.65	1.99
Biomass (t ha^{-1})	91	2.78	3.75	0.39	2	3.56

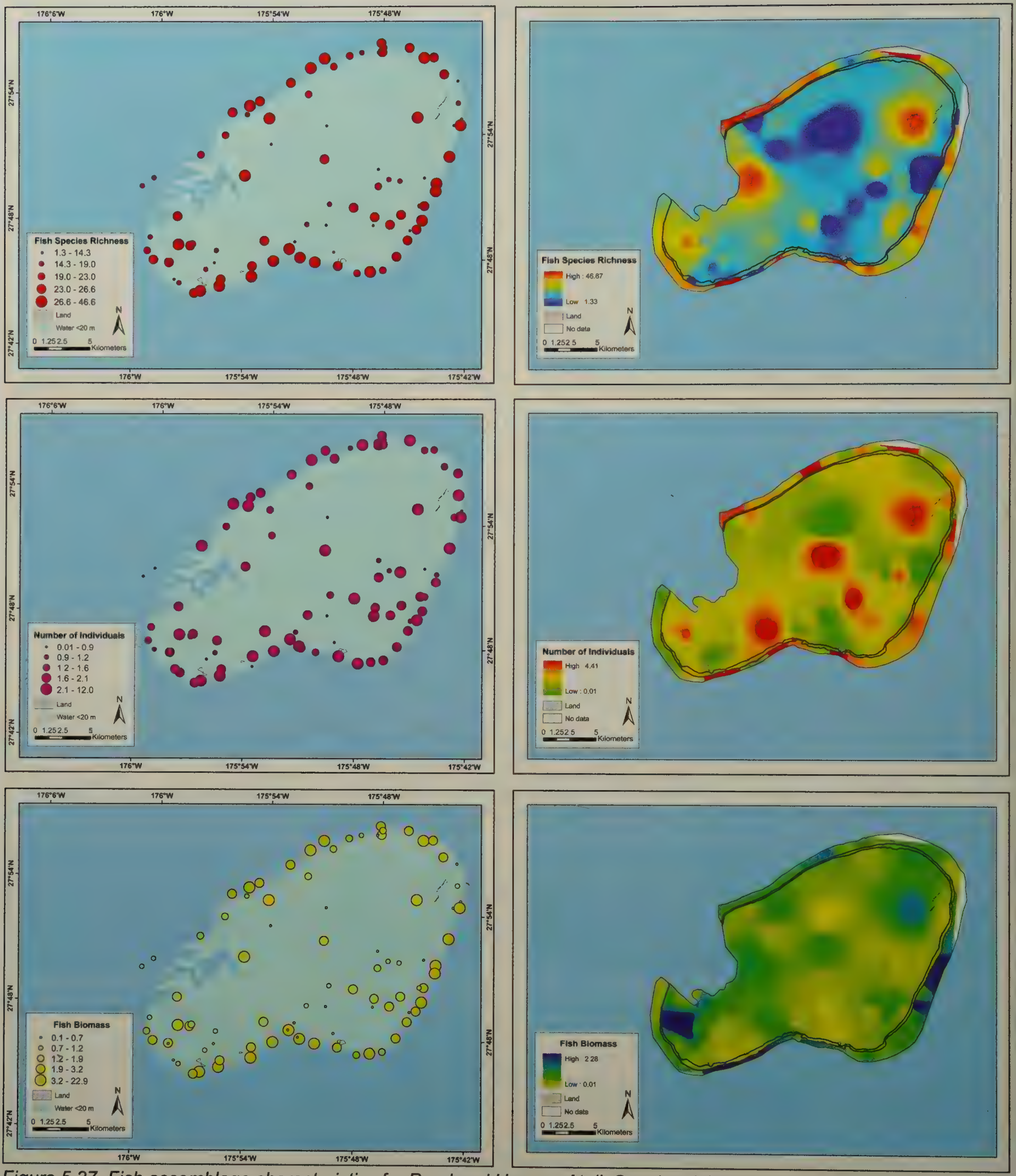


Figure 5.37. Fish assemblage characteristics for Pearl and Hermes Atoll. Species richness (top row), number of individuals (middle row) and biomass (t ha^{-1}, bottom row). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

The numerical density of fishes at Pearl and Hermes ranked second overall ($\bar{x}$ = 1.8, SD ± 0.8). Overall, planktivores comprised a third (37%) of total density, which included oval chromis (11%) blackfin chromis (7%) and chocolate dip chromis (*Chromis hanui*, 5%). The number of individuals observed on the fore reef ($\bar{x}$ = 2.1, SD ± 0.9) was significantly higher ($p<0.05$) than the back reef ($\bar{x}$ = 1.9, SD ± 0.6) and lagoon ($\bar{x}$ = 1.6, SD ± 0.8) habitats.

Table 5.24. Fish assemblage characteristics for Pearl and Hermes Atoll for each major habitat type. Source: NWHI RAMP, unpub. data.

BACK REEF	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	7	17	4.59	1.74	12.75	21.25
Number of Individuals (m^2)	7	1.88	0.55	0.21	1.37	2.39
Biomass (t ha^{-1})	7	1.05	0.85	0.32	0.26	1.83
LAGOON						
Species	43	16.91	5.99	0.91	15.07	18.76
Number of Individuals (m^2)	43	1.63	0.78	0.12	1.39	1.87
Biomass (t ha^{-1})	43	2.02	3.02	0.46	1.09	2.95
FORE REEF						
Species	41	24.02	6.91	1.08	21.84	26.2
Number of Individuals (m^2)	41	2.01	0.88	0.14	1.73	2.29
Biomass (t ha^{-1})	41	3.88	4.42	0.69	2.49	5.28

Pearl and Hermes ranked first in fish biomass on the fore reefs ($\bar{x}$ = 3.9, SD± 4.4) among all locations. Biomass was significantly higher on the fore reef ($p < 0.05$) than the lagoon ($\bar{x}$ = 2.0, SD ± 3.0), which, in tern, was significantly higher ($p < 0.05$) than at back reef ($\bar{x}$ = 1.0, SD± 0.9). Apex predators dominated the fish biomass, with giant trevally accounting for 48%, followed by whitetip reef sharks (6%), and Galapagos sharks (5%). Stations with the highest biomass were located along the leeward, southwest fore reef.

Midway Atoll

Midway ranked fifth in species richness among all reef locations (Table 5.25, Figure 5.38). The mean number of species per transect differed significantly ($p<0.05$) among all three habitats. Fore reef habitats harbored 27.0 (SD ± 6.0) species, followed by back reefs ($\bar{x}$ = 19.1, SD ± 4.8), and lagoon habitats ($\bar{x}$ = 15.8, SD ± 6.1). Richness was highest along the southern fore reef (Table 5.26).

Midway ranked first in numerical density ($\bar{x}$ = 2.7 individuals/m^2, SD ± 2.0). The lagoon harbored the greatest number of individuals ($\bar{x}$ = 2.9 individuals/m^2, SD ± 2.7) consisting of damselfishes (oval chromis – 11%, Pacific Gregory – 10%, domino damselfish – 5%, blackfin chromis – 5% and chocolate dip chromis – 5%). All except the Pacific Gregory are planktivores. Saddle wrasse (13%) and schools of convict tangs (6%) also contributed to the large number of individuals observed at Midway. Numerical abundance was highest on the northwestern leeward fore reef and in Welles Harbor.

Table.5.25. Fish assemblage characteristics for Midway Atoll across all habitat types. Source: NWHI RAMP, unpub. data.

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	37	21.59	7.97	1.31	18.94	24.25
Number of Individuals (m^2)	37	2.69	2.04	0.34	2.01	3.37
Biomass (t ha^{-1})	37	2.5	2.14	0.35	1.78	3.21

Table 5.26. Fish assemblage characteristics for Midway Atoll for each major habitat type. Source: NWHI RAMP, unpub. data.

BACK REEF	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	4	19.08	4.79	2.4	11.45	26.71
Number of Individuals (m^2)	4	1.59	0.46	0.23	0.85	2.32
Biomass (t ha^{-1})	4	1.46	0.65	0.33	0.42	2.49
LAGOON						
Species	15	15.76	6.14	1.59	12.35	19.16
Number of Individuals (m^2)	15	2.9	2.69	0.69	1.41	4.39
Biomass (t ha^{-1})	15	1.58	1.22	0.31	0.91	2.26
FORE REEF						
Species	18	27.02	6.05	1.43	24.01	30.03
Number of Individuals (m^2)	18	2.76	1.58	0.37	1.97	3.54
Biomass (t ha^{-1})	18	3.49	2.52	0.59	2.24	4.74

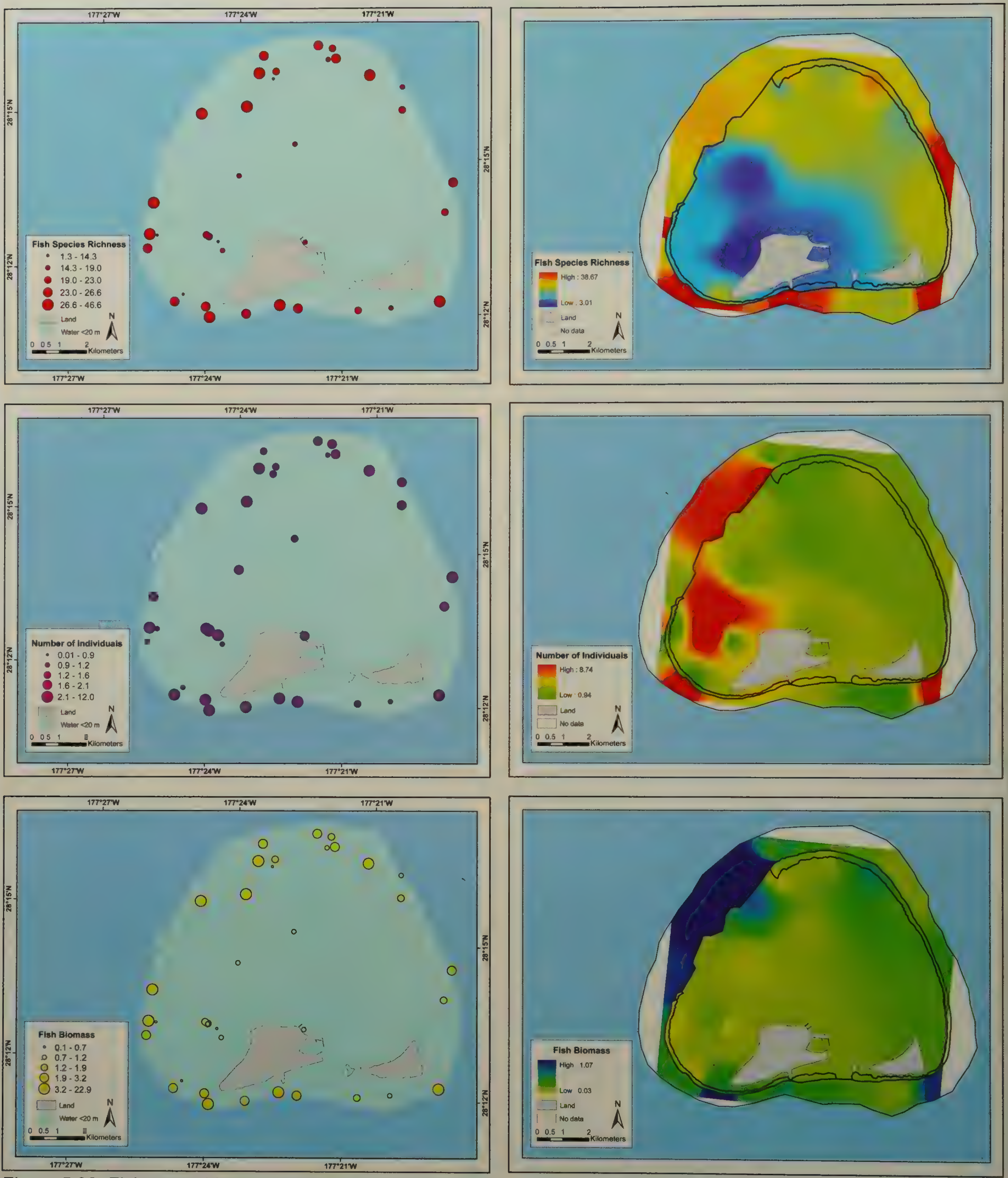


Figure 5.38. Fish assemblage characteristics for Midway Atoll. Species richness (top row), number of individuals (middle row) and biomass (t ha^{-1}; bottom row). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

Biomass at Midway averaged 2.5 t ha^{-1} (SD ±2.1) and ranked second overall among locations. There were large differences in biomass among habitat types with biomass on the fore reef ($\bar{x}$ = 3.5, SD ± 2.5) more than two times higher than the back reef ($\bar{x}$ = 1.5, SD ± 0.7), and the lagoon ($\bar{x}$ = 1.6, SD ± 1.2). Herbivores accounted for the majority of the biomass (57%) with considerable contributions from the spectacled parrotfish (13%), whitebar surgeonfish (8%), convict tang (7%), and bluespine unicornfish (6%). Galapagos sharks (8%) and giant trevally (5%) were the major predators by weight. The highest biomass was observed along the northwest fore reef where the reef crest becomes submerged and along the southern fore reef off Sand Island.

Kure Atoll

Species richness at Kure was low ($\bar{x}$ = 19.6, SD ± 6.3) ranking eighth overall (Table 5.27, Figure 5.39). Significantly higher ($p<0.05$) numbers of species were observed on the fore reef ($\bar{x}$ = 21.5, SD ± 6.3) compared to the lagoon ($\bar{x}$ = 17.4, SD ± 6.0) and back reef ($\bar{x}$ = 15.3, SD ± 2.0). Richness was high around the entire fore reef (Table 5.28).

Table 5.27. Fish assemblage characteristics for Kure Atoll across all habitat types. Source: NWHI RAMP, unpub. data.

LEVEL	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	59	19.6	6.32	0.82	17.96	21.25
Number of Individuals (m^{2})	59	1.41	0.81	0.1	1.2	1.62
Biomass (t ha^{-1})	59	1.22	1.13	0.15	0.93	1.51

An average of 1.4 individuals/m^{-2} were observed at Kure (sixth overall). Saddle wrasse (20%), oval chromis (12%), Pacific Gregory (9%) and chubs (6%) were most important numerically. No strong patterns in the distribution of individuals was observed and no significant difference among habitat types ($p>0.05$) were detected. The fore reef averaged 1.6 individuals/m^{-2}, followed by lagoon ($\bar{x}$ = 1.3, SD ± 1.1) and back reef ($\bar{x}$ = 1.1, SD ± 0.2). Fish density was highest on the leeward fore reef and central western patch reefs.

Table 5.28. Fish assemblage characteristics for Kure Atoll for each major habitat type. Source: NWHI RAMP, unpub. data.

BACK REEF	NUMBER	MEAN	STD DEV	STD ERR MEAN	LOWER 95%	UPPER 95%
Species	5	15.27	2.05	0.92	12.73	17.81
Number of Individuals (m^{2})	5	1.11	0.21	0.09	0.85	1.37
Biomass (t ha^{-1})	5	0.61	0.19	0.09	0.38	0.85
LAGOON						
Species	20	17.42	5.96	1.33	14.63	20.21
Number of Individuals (m^{2})	20	1.31	1.09	0.24	0.8	1.82
Biomass (t ha^{-1})	20	1.22	1.53	0.34	0.5	1.94
FORE REEF						
Species	34	21.53	6.3	1.08	19.33	23.73
Number of Individuals (m^{2})	34	1.52	0.65	0.11	1.29	1.75
Biomass (t ha^{-1})	34	1.31	0.91	0.16	0.99	1.63

Kure had the second lowest biomass of any location ($\bar{x}$ = 1.2, SD ± 1.1) and the lowest proportion of apex predators (16%). Spectacled parrotfish (17%), chubs (10%) and giant trevally (5%) were most important by weight. There were no strong patterns in the spatial distribution of biomass. Unlike other locations, the lagoon ($\bar{x}$ = 1.2, SD ± 1.5) and fore reef ($\bar{x}$ = 1.3, SD ± 0.9) biomass estimates were very similar.

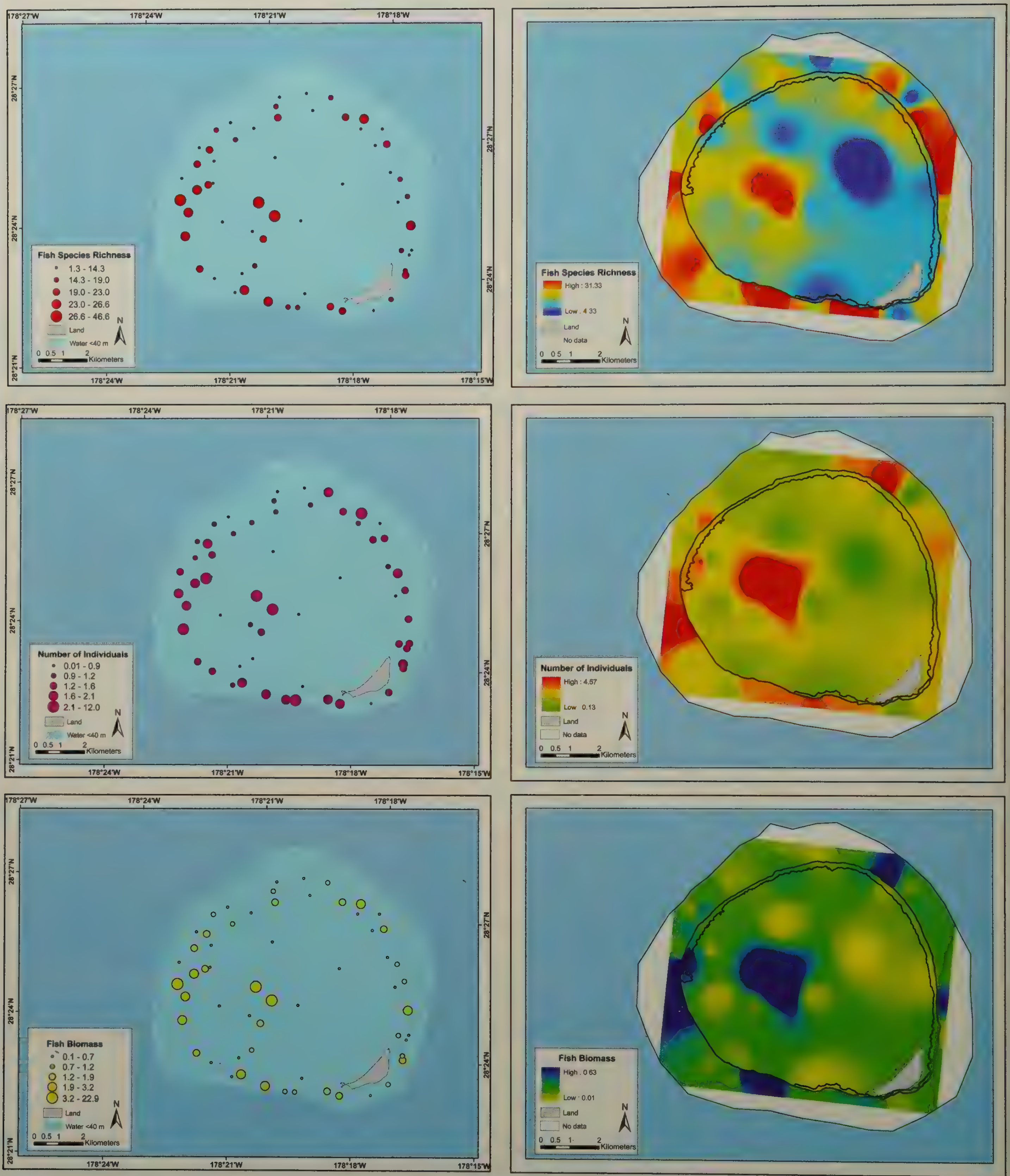


Figure 5.39. Fish assemblage characteristics for Kure Atoll. Species richness (top row), number of individuals (middle row) and biomass (t ha^{-1}; bottom row). Source: NWHI RAMP, unpub. data; maps: L. Wedding.

EXISTING DATA GAPS

Two major issues dominate the management and conservation of reef resources in the NWHI and throughout the Hawaiian Archipelago. The dispersal, connectivity, and genetic exchange between reef populations of NWHI and MHI organisms is undoubtedly the issue of greatest consequence for future management and conservation of reef fish and other resources in the NWHI as well as the MHI. Much recent progress has been made obtaining the empirical data needed to begin unraveling patterns of planktonic dispersal and more directed adult movements of fishes in the NWHI (see the Connectivity and Integrated Ecosystem Studies chapter of this document). The habitat relations of fishes are arguably the second most important issue to consider for fishes in the NWHI. Habitat alterations (sea level rise, warming, acidification) resulting from global climate change are expected to be the most significant impacts and likely to occur in the NWHI (Selkoe et al., 2008). Although the effects of global warming and coral bleaching on coral reef fishes are of concern worldwide (Pratchett et al., 2008a), they are relatively more important in the NWHI where resources are now protected from other human impacts by establishment of the Monument.

The prevalence and dynamics of coral and related substrata (e.g., algal secondary cover) represent the most obvious habitat issues for shallow-water reef fishes in the NWHI. Although corals are important as a food source only for relatively few, specialized fishes in tropical reef ecosystems including Hawaii (Cole et al. 2008), corals provide exceedingly important shelter resources (Caley and St. John, 1996). These shelter resources are especially important for the relatively small-bodied and predator-vulnerable juvenile life stages of reef fishes, particularly early YOY near the time when they settle from the plankton as "recruits" to benthic populations (Jones et al., 2004; DeMartini and Anderson, 2007). Coral shelter is nonetheless also important for larger, older juveniles and adults (Beukers and Jones, 1997).

A comprehensive and systematic characterization of the habitat relations of Hawaiian reef fishes is lacking and needed. The only published work to date is limited to finger coral habitat on shallow (10 m) fringing reefs of the leeward Big Island and further restricted to the recruits of a suite of summer-recruiting species, primarily tangs of the family Acanthuridae (DeMartini and Anderson, 2007). Work is in progress to expand this catalogue both taxonomically and across additional habitats, with initial emphasis on the diverse labroids (parrotfishes, wrasses) that recruit in spring-summer to very shallow (1-3 m deep) and wave-protected coral rubble habitats. Several recent case studies exemplify the need for distinguishing habitat relations between juvenile and adult conspecifics (Pratchett et al., 2008b; Wellenreuther and Clements, 2008). For this reason, the habitat relations of adult as well as juvenile Hawaiian reef fishes are being described.

REFERENCES

Allen, G.R. 2002. Indo-Pacific coral-reef fishes as indicators of conservation hotspots. Proc 9th Int Coral Reef Symp 2: 921-926.

Beukers J.S. and G.P. Jones. 1997. Habitat complexity modifies the impact of piscivores on a coral reef fish population. Oecologia 114: 50-59.

Burridge, C.P. and R.W.G. White. 2000. Molecular phylogeny of the antitropical subgenus *Goniistius* (Perciformes: *Cheilodactylidae*: Cheilodactylus): evidence for multiple transequatorial divergences and non-monophyly. Biol J Linn Soc 70: 435–458.

Caley, M.J. and J. St. John. 1996. Refuge availability structures assemblages of coral reef fishes. J Anim Ecol 65: 414-428.

Cole, A.J., M.S. Pratchett, and G.P. Jones. 2008. Diversity and functional importance of coral-feeding fishes on tropical coral reefs. Fish and Fisheries 9: 286-307.

Cowen, R.K., C.B. Paris, and A. Srinivasan. 2006. Scaling of connectivity in marine populations. Science 311: 522-527.

DeMartini, E.E. 2004. Habitat and endemism of recruits to shallow reef fish populations: selection criteria for no-take MPAs in the NWHI Coral Reef Ecosystem Reserve. Bull Mar Sci 14: 185–205.

DeMartini, E.E. and T.W. Anderson. 2007. Habitat associations and aggregation of recruit fishes on Hawaiian coral reefs. Bull Mar Sci 81: 139-152.

DeMartini, E.E. and A.M. Friedlander. 2004. Spatial pattern of endemism in shallow water reef fish populations of the Northwestern Hawaiian Island. Mar. Ecol. Prog. Ser. 271: 281-296.

DeMartini, E.E. and A.M. Friedlander. 2006. Predation, endemism, and related processes structuring shallow-water reef fish assemblages of the NWHI. Atoll Research Bulletin 543: 237-257.

DeMartini E.E., A.M. Friedlander, and S.R. Holzwarth. 2005. Size at sex change in protogynous labroids, prey body size distributions, and apex predator densities at NW Hawaiian atolls. Marine Ecology Progress Series 297: 259-271.

DeMartini, E.E., F.A. Parrish, and R.C. Boland. 2002. Comprehensive evaluation of shallow reef fish populations at French Frigate Shoals and Midway Atoll, Northwestern Hawaiian Islands (1992/93, 1995–2000). NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-347NOAA Fisheries, Southwest Fisheries Science Center, Honolulu.

DeMartini, E.E., B.J. Zgliczynski, R.C. Boland, and A.M. Friedlander. In review. Influences of wind-wave exposure on the distribution and density of recruit reef fishes at Kure and Pearl and Hermes atolls, Northwestern Hawaiian Islands. Environ. Biol. Fish.

Ehler, R. 2004. Socio-economic assessment of commercial bottomfishing in the Northwestern Hawaiian Islands. Report to NOAA,NOS, National Marine Sanctuary Program. Pp 46.

Friedlander, A.M., and E. Brown . 2004.Marine Protected Areas and community-based fisheries management in Hawaii. Pp. 208-230. In: A.M. Friedlander (ed.), Status of Hawaii's Coastal Fisheries in the New Millenium. 2nd ed. Proceedings 2001 Fisheries Symposium sponsored by the American Fisheries Society, Hawaii Chapter. Honolulu, Hawaii.

Friedlander A.M., E.K. Brown, and M.E. Monaco. 2007. Coupling ecology and GIS to evaluate efficacy of marine protected areas in Hawaii. Ecol. Appl. 17: 715-30.

Friedlander, A.M. and E.E. DeMartini. 2002. Contrasts in density, size, and biomass of reef fishes between the Northwestern. and the Main Hawaiian Islands: the effects of fishing down apex predators. Mar. Ecol. Prog. Ser. 230: 253-264.

Gray, J.S. 1997. Marine biodiversity: patterns, threats and conservation needs. Biodiversity and Conservation 6:153-175.

Hawkins, J.P., C.M. Roberts, and V. Clark. 2000. The threatened status of restricted range coral reef fish species. Anim Conserv 3: 81–88.

Jones, G.P., M.I. McCormick, M. Srinivasan, and J.V. Eagle. 2004. Coral decline threatens fish biodiversity in marine reserves. Proc Nat Acad Sci USA 101: 8251-8253.

Maragos, J., D. Potts, G. Aeby, D. Gulko, J. Kenyon, D. Siciliano, and D. VanRavensway. 2004. 2000-2002 Rapid Ecological Assessment of Corals (Anthozoa) on shallow reefs of the Northwestern Hawaiian Islands, Part I: Species and Distribution. Pacific Science 58(2): 211-230.

Mundy, B.C. 2005. Checklist of the fishes of the Hawaiian archipelago. Bishop Museum Bulletin in Zoology 6. Bishop Museum Press, Honolulu, Hawaii.

Papastamatiou, Y.P., B.M. Wetherbee, C. Lowe, and G.L. Crow. 2006. Distribution and diet of four species of carcharhinid shark in the Hawaiian Islands: evidence for resource partitioning and competitive exclusion. Mar. Ecol. Pro. Ser. 320: 239-251.

Pratchett, M.S., M.L. Berumen, M.J. Marnane, J.V. Eagle, and D.J. Pratchett. 2008. Habitat associations of juvenile versus adult butterflyfishes. Coral Reefs 27: 541-551.

Pratchett, M.S., P.L. Munday, S.K. Wilson, N.A.J. Graham, J.E. Cinner, D.R. Bellwood, G.P. Jones, N.V.C. Polunin, and T.R. McClanahan. 2008. Effects of climate induced coral bleaching on coral-reef fishes — ecological and economic consequences. Oceanogr Mar Biol Annu Rev 46: 251-296.

Randall, J.E. 1981. Examples of antitropical and antiequatorial distribution of Indo-West-Pacific fishes. Pac Sci 35: 197–209.

Randall, J.E. 1987. Introductions of marine fishes to the Hawaiian Islands. Bull Mar Sci 41: 490-502.

Randall J.E. 1995. Zoogeographic analysis of the inshore Hawaiian fish fauna. Pp:193-203. In: Maragos J.E., Peterson M.N.A., Eldredge L.G., Bardach J.E., and Takeuchi H.F. (eds.) Marine and coastal biodiversity in the tropical island Pacific region: Vol. 1, Species systematics and information management priorities. East-West Center, Honolulu.

Randall J.E. 1998. Zoogeography of shore fishes of the Indo-Pacific region. Zool Stud (Taiwan) 37: 227–268.

Randall J.E. 2007. Reef and shore fishes of the Hawaiian Islands. Sea Grant College Program, University of Hawaii, Honolulu. 546 pp.

Randall J.E., and J.L. Earle. 2000. Annotated checklist of the shore fishes of the Marquesas Islands. Occas Pap Bishop Museum 66: 1–39.

Randall, J.E., J.L. Earle, R.L. Pyle, J.D. Parrish, and T. Hayes. 1993. Annotated checklist of the fishes of Midway Atoll, Northwestern Hawaiian Islands. Pac Sci 47: 356–400.

Roberts, C.M., C.J. McClean, J.E.N. Veron, J.P. Hawkins and 8 others. 2002. Marine biodiversity hotspots and conservation priorities for tropical reefs. Science 295: 1280–1284.

Selkoe, K.A., B.S. Halpern, and R. Toonen. 2008. Evaluating anthropogenic threats to the Northwestern Hawaiian Island Aquatic Conservation: Marine and Freshwater Ecosystems 18:1149-1165.

Wellenreuther, M. and K.D. Clements 2008. Determinants of habitat association in a sympatric clade of marine fishes. Mar Biol 154: 393-402.

Williams, I.D., W.J. Walsh, R.E. Schroeder, A.M. Friedlander, B.L. Richards, and K.A. Stamoulis. 2008. Assessing the importance of fishing impacts on Hawaiian coral reef fish assemblages along regional-scale human population gradients. Environ Conserv 35: 261-272.

Marine Protected Species

Charles Littnan[1], Marie (Chapla) Hill[2], Stacy (Kubis) Hargrove[1], Kaylene E. Keller[3] and Angela D. Anders[4]

INTRODUCTION

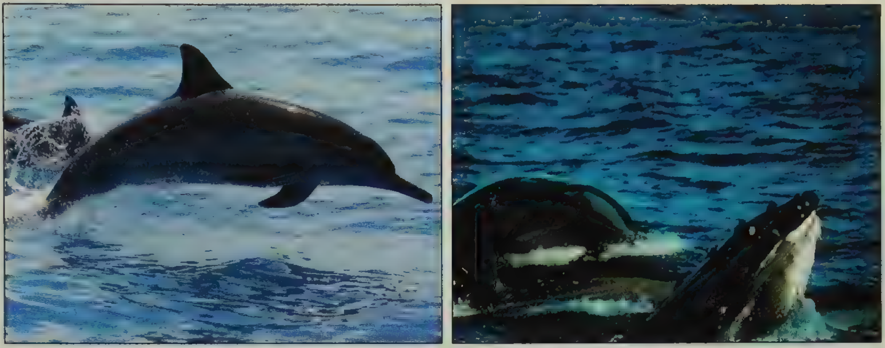


Figure 6.1. The Monument protects habitat for many marine mammal species, including several species of dolphins and whales. A spinner dolphin (left) and humpback whales (right) are pictured here. Photos: PIFSC and D. Shapiro.

The Monument protects habitat for many marine mammal species ,including 24 species of cetaceans that have been sighted in the Hawaiian Islands Exclusive Economic Zone (EEZ), and the critically endangered Hawaiian monk seal. (Figure 6.1). Twenty three species of cetaceans were observed and identified to the species level during a 2002 survey (Barlow et al., 2004). Four of these species are on the U.S. Endangered Species list, including the humpback whale (*Megaptera novaeangliae*), sperm whale (*Physeter macrocephalus*), fin whale (*Balaenoptera physalus*) and sei whale (*Balaenoptera borealis*; http://www.nmfs.noaa.gov/pr/species/esa/mammals.htm). In addition, the false killer whale (*Pseudorca crassidens*) is listed as a strategic stock under the 1994 amendments to the Marine Mammal Protection Act (MMPA). Each of these species has been observed within the Monument boundaries (Barlow et al., 2004; Johnston et al., 2007; NMFS, unpublished data). Several of the cetacean species observed within the Hawaiian Islands EEZ are found there year-round (e.g., spinner dolphins, false killer whales, rough-toothed dolphins). Others occur there only seasonally and in some cases are known to migrate long distances to use the area for breeding (e.g., humpback whales).

Figure 6.2. The Monument is home to the six primary Hawaiian monk seal subpopulations (left). The area also protects nesting habitat of the green turtle (right). The Hawaiian monk seal is listed as endangered and the green turtle is listed as threatened under the U.S. Endangered Species Act. Photos: J. Watt.

In addition to providing important habitat to cetaceans, the Monument is also the primary habitat for the federally endangered Hawaiian monk seal (*Monachus schauinslandi;* Figure 6.2*)*. The six main Hawaiian monk seal subpopulations are completely contained within the Monument boundaries. The Hawaiian monk seal population is estimated to have declined by 60% since the 1950s (Antonelis et al., 2006), and is currently estimated at just under 1,200 individuals. Because of its small population size and swift rate of decline, the Hawaiian monk seal is the focus of intense conservation efforts.

Finally, the Monument provides the primary nesting habitat for the green turtle (*Chelonia mydas*; Figure 6.2) in the Hawaiian Archipelago, listed as Threatened under the U.S. Endangered Species Act (ESA). Green, loggerhead (*Caretta caretta*), hawksbill (*Eretmochelys imbricata*), leatherback (*Dermochelys coriacea*) and

---

1. NOAA/NMFS/Pacific Islands Fisheries Science Center
2. Joint Institute for Marine and Atmospheric Research
3. NOAA/NOS/ONMS/Papahanaumokuakea Marine National Monument
4. Clancy Environmental Consultants, Inc.

olive ridley (*Lepidochelys olivacea*) turtles use the Monument for foraging habitat and as migration pathways. Although the Hawaiian green turtle population has been increasing over the past three decades, individuals still nest primarily at French Frigate Shoals in the Northwestern Hawaiian Islands (NWHI).

CETACEANS

Available Data

Most of what is known about cetaceans found within the Hawaiian EEZ comes from data collected within the waters surrounding the Main Hawaiian Islands (MHI). Although somewhat limited, information on the occurrence of cetacean species within the Monument comes from historical whaling records, documented opportunistic sightings and stranding records, data collected during ship-based surveys, and species-specific (e.g., spinner dolphin) photo-identification and genetic research.

Charles Townsend (1935) used whaling logbooks to record locations of certain whale species onto charts of both the Atlantic and Pacific Oceans. The Wildlife Conservation Society digitized the charts and made them available to the general public (http://www.wcs.org/sw-high_tech_tools/landscapeecology/townsend_charts). Data on sperm whale sightings within the Hawaiian EEZ, including the Monument, are extracted from these records (see Species Descriptions section, sperm whale).

Edward W. Shallenberger (1981) collected information from published and unpublished literature, field notes, ships' logs, and interviews with knowledgeable people in order to document the occurrence and status of cetacean species found in Hawaiian waters, including the NWHI.

The *Atoll Research Bulletin* produced a series of publications on the natural history of the NWHI in which records of cetacean species were documented from opportunistic sightings and stranding events (Rice, 1960; Amerson, 1971; Woodward, 1972; Amerson et al., 1974; Nitta and Henderson, 1993). These records are more anecdotal in nature and lack precise location data (i.e., latitude/longitude points), however, they are useful for generalizing about the occurrence of certain species within the Monument.

Precise data regarding the occurrence of cetaceans in the Monument come from recent ship-based surveys within the 200 nm EEZ surrounding the Hawaiian Islands (Barlow et al., 2004; Johnston et al., 2007; NMFS, unpublished data). In 2002, Barlow et al. (2004) conducted standard ship-based visual line-transect surveys, from two ships, for all cetacean species in the Hawaiian Islands EEZ. Search effort included a total of 24,738 km (13,357 nm) over 157 survey days. Acoustic monitoring, photo-documentation, biopsy and behavioral studies were conducted concurrently. Line-transect surveys resulted in observations of 23 cetacean species within the Hawaiian Islands EEZ, with 15 of those species seen within the boundaries of the Monument (see Species Descriptions section and Figure 6.3; Barlow et al., 2004). Abundance estimates and densities per 1,000 km^2 were calculated for 19 of the 23 cetacean species observed (Table 6.1; see Cetaceans Abundance Estimates section on page 210; Barlow, 2006).

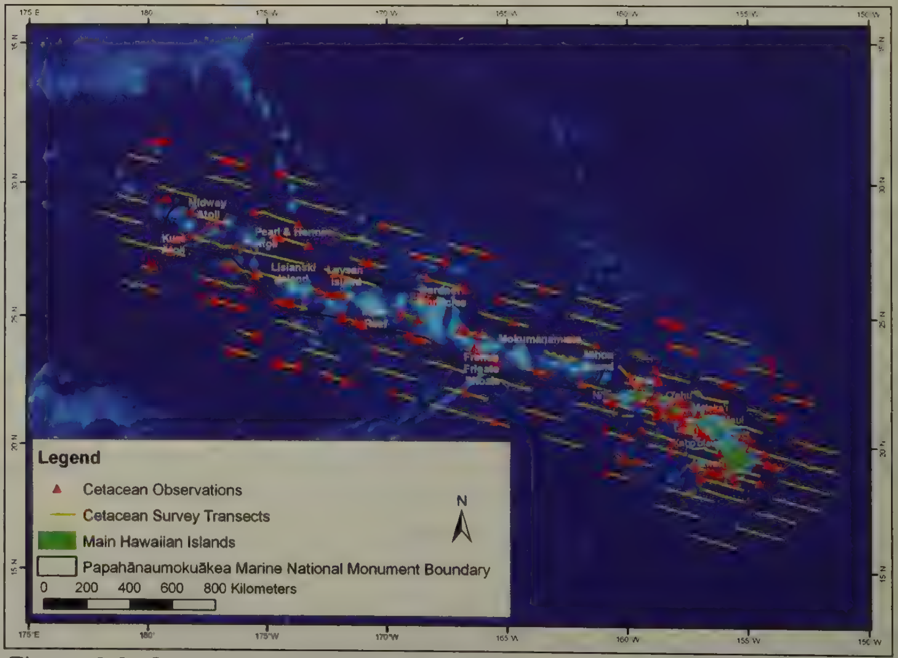


Figure 6.3. Cetacean Observations and Survey Transects . Sources: Barlow et al., 2004; Johnston et al., 2007; NMFS, unpublished; Townsend, 1935; map: K. Keller.

Table 6.1. Estimated abundance of 19 cetacean species in the MHI and outer Hawaiian Islands EEZ. Overall abundances, overall densities, and coefficients of variation (CV) are pooled from the MHI and outer EEZ estimates. Pooled abundance and density estimates are given for delphinids and beaked whales. Asterisk (*) indicates a more recent estimate of false killer whale abundance in offshore waters of the Hawaiian EEZ (484 individuals, CV=0.93) comes from Barlow and Rankin (2007). Source: Barlow, 2006.

SPECIES	MAIN ISLAND ABUNDANCE (n)	OUTER EEZ ABUNDANCE (n)	OVERALL ABUNDANCE (n)	OVERALL DENSITY PER 1,000 km^2 (D)	CV
Offshore spotted dolphin	4,283	4,695	8,978	3.66	0.48
Striped dolphin	660	12,483	13,143	5.36	0.46
Spinner dolphin	1,488	1,863	3,351	1.37	0.74
Rough-toothed dolphin	1,713	6,997	8,709	3.55	0.45
Bottlenose dolphin	465	2,750	3,215	1.31	0.59
Risso's dolphin	513	1,859	2,372	0.97	0.65
Fraser's dolphin	0	10,226	10,226	4.17	1.16
Melon-headed whale	0	2,950	2,950	1.20	1.17
Pygmy killer whale	956	0	956	0.39	0.83
False killer whale *	0	236	236	0.10	1.13
Short-finned pilot whale	3,190	5,680	8,870	3.62	0.38
Killer whale	0	349	349	0.14	0.98
Sperm whale	126	6,793	6,919	2.82	0.81
Pygmy sperm whale	0	7,138	7,138	2.91	1.12
Dwarf sperm whale	0	17,519	17,519	7.14	0.74
Blainville's beaked whale	0	2,872	2,872	1.17	1.25
Cuvier's beaked whale	0	15,242	15,242	6.21	1.43
Longman's beaked whale	0	1,007	1,007	0.41	1.26
Bryde's whale	0	469	469	0.19	0.45
Delphinids pooled	13,267	50,087	63,354	25.83	
Beaked whales pooled	371	19,121	19,492	7.95	

The work of Johnston et al. (2007) focused on visual and acoustic observations of humpback whales from Oahu to Midway Atoll in the NWHI during March and April 2007. Search effort covered 1,690 km over 12 survey days. Surveys were focused on areas near atolls and islands, and tracklines generally followed the 183 m (1,000 fathom) isobath, however, some tracklines were in deeper waters (Johnston et al., 2007; NMFS, unpublished data). Observations were conducted following standard distance sampling/line transect methods for cetaceans, similar to those employed in Barlow et al. (2004). During the surveys, sightings of all cetaceans were recorded, including location and group size estimates (NMFS, unpublished data). Additionally, acoustic monitoring, photo-documentation and biopsy sampling were conducted. These surveys resulted in the detection of 44 groups of eight cetacean species. Seven of these species were observed within Monument boundaries (Johnston et al., 2007; NMFS, unpublished data). In the Species Description section (below) these surveys will be referred to as the NWHI survey.

Other species-specific cetacean work within the Monument includes research on the social patterns and population structure of spinner dolphins (*Stenella longirostris*) at Midway Atoll (Karczmarski et al., 1998; 1999; Rickards et al., 2001; Karczmarski et al., 2005) and the genetic diversity of spinner dolphins within the Hawaiian Archipelago (Andrews et al., 2006). The photo-identification and behavioral research at Midway Atoll consisted of land and small boat-based surveys conducted in 1998 through 2001, totaling 1,104 effort hours. Results of this work indicate that a resident spinner dolphin population is present at Midway, but that movement of individuals between Midway, Kure Atoll, and Pearl and Hermes Atoll occurs (Karczmarski et al., 1998; 1999; Rickards et al., 2001; Karczmarski et al., 2005). The analysis of biopsy samples taken from various locations within the Hawaiian Archipelago (e.g., Hawaii, Maui/Lanai, Oahu, Niihau, French Frigate Shoals, Pearl and Hermes Atoll, Midway Atoll and Kure Atoll) indicates a genetic distinction among separate spinner dolphin populations (Andrews et al., 2006).

Species Descriptions

Description, range and habitat information is taken from the following sources: Tomich (1986), Ridgeway and Harrison (1994), Ridgeway and Harrison (1999), Perrin et al. (2002), Reeves et al. (2002), and OBIS SEAMAP (an online data source that compiles information from various published sources, http://seamap.env.duke.edu/).

Offshore Pantropical Spotted Dolphin (*Stenella attenuata*)

Three subspecies of the pantropical spotted dolphin are recognized worldwide and differ in body size, coloration and skull characteristics. Their lengths range from 1.6 m to 2.6 m and their average weight is 114 kg. In general, the pantropical spotted dolphin has a moderately slender body; a relatively small dorsal fin that is strongly falcate (back-curved or shaped like a sickle); and a long, slender beak. The basic color pattern includes a dark gray dorsal cape that dips low onto the sides below and forward of the dorsal fin and a lighter gray ventral (belly) color that widens along the sides of the peduncle, or tailstock. Adults have a black "mask" and a dark jaw-to-flipper stripe. The pattern of spotting and striping on adults can be extremely complex and variable; in Hawaii animals have very little dorsal spotting. Calves are born without spots, and juveniles develop them first on their ventral side. The tip of the beak is white and more conspicuous in some populations, including those found in the waters surrounding the Hawaiian Archipelago.

Pantropical spotted dolphins are found in all tropical to warm temperate oceanic waters between 40°N and 40°S. In the Pacific Ocean, the stocks are separated into the offshore eastern tropical Pacific, the coastal waters between Baja California and the northwestern coast of South America, and the near-shore waters around the Hawaiian Islands.

Pantropical spotted dolphins are found throughout the Hawaiian Archipelago and are common on the leeward sides of the islands as well as at shallow offshore banks (Shallenberger, 1981; Tomich, 1986). A series of 12 aerial surveys (1993-1998) within 46 km of the coastline surrounding the MHI resulted in observations of 23 groups of spotted dolphins, with an average size of 42.8 individuals (Mobley et al., 2000). Baird et al. (2003) recorded 25 sightings around the MHI in May and June of 2003 with a mean group size of 77.1 individuals. Baird et al. (2006) determined that the peak in sighting rates off the MHI occurred in water depths of 1,000-2,000 m. Within the Hawaiian EEZ, during the 2002 (August –November) ship-based survey, Barlow et al. (2004) recorded 12 sightings of spotted dolphins in groups as large as 80 individuals (Figure 6.4). One sighting of 74 individuals occurred within the Monument boundaries (Barlow et al., 2004).

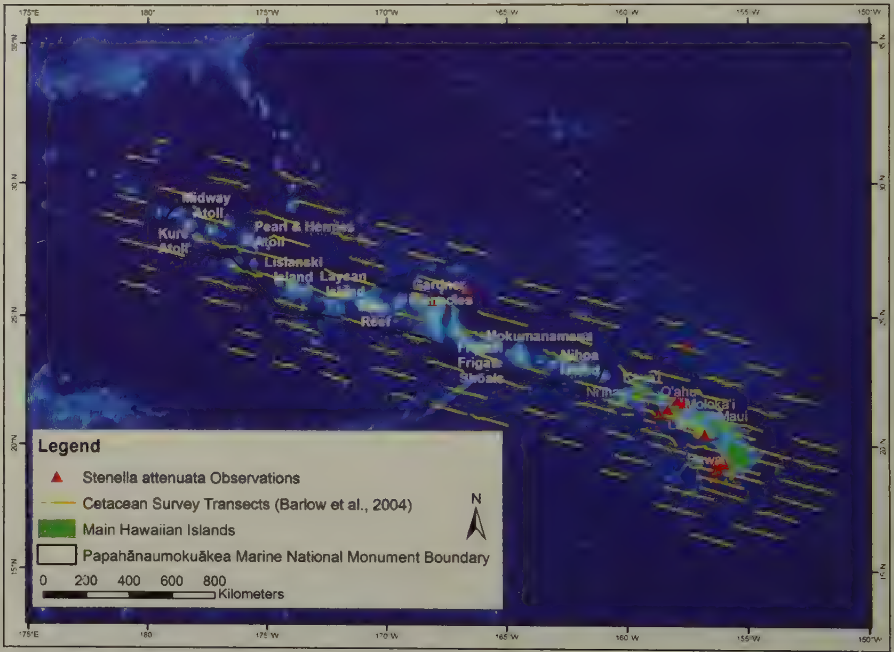


Figure 6.4. Pantropical spotted dolphin observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Striped Dolphin (*Stenella coeruleoalba*)

The striped dolphin reaches a maximum length of 2.7 m and a maximum weight of 160 kg. It has a small to medium-sized robust body; a prominent falcate dorsal fin; and a long, well-defined beak. The color pattern is a combination of bluish-gray and white. The cape, beak, fins and tail are dark blue-gray. The ventral side, or belly, is white. On each side of the body a narrow black stripe runs from the beak to the eye and then diverges; one branch runs from to the pectoral flipper and the other continues along the side to the anal region. A bluish or light gray shoulder blaze is present above the side stripe and below and anterior to the dorsal fin. The markings and boldness of the stripes vary with individual and geographical location.

Striped dolphins are primarily found in tropical and warm temperate waters that are oceanic and deep from 50°N to 40°S. They occur in the U.S. off the west coast, in the northwestern Atlantic, in the Gulf of Mexico and in the waters off of the Hawaiian Islands. This species associates with upwelling areas and convergence zones.

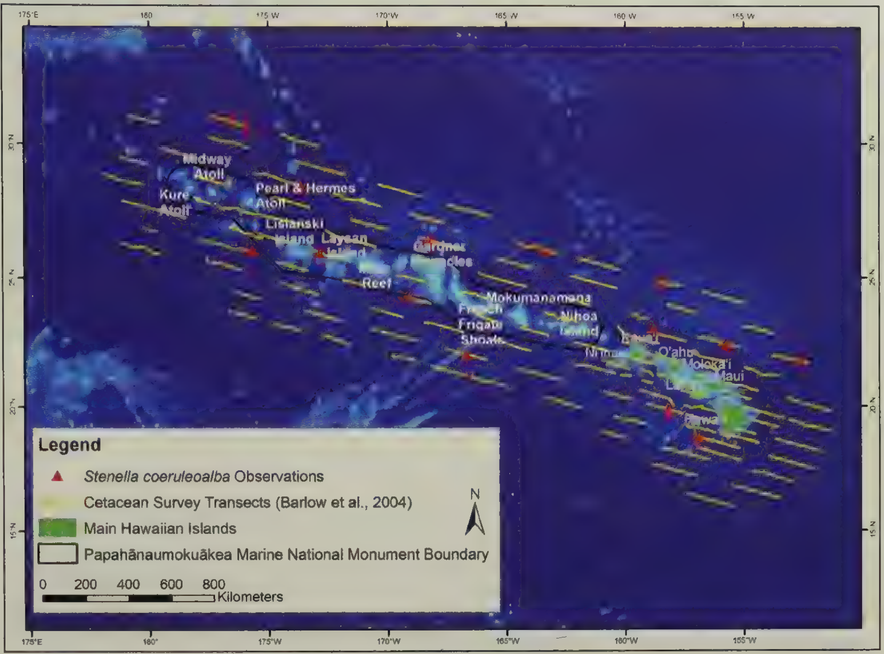


Figure 6.5. Striped dolphin observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Striped dolphins are considered rare in Hawaiian waters (Shallenberger ,1981; Tomich, 1986). Baird et al. (2005a) suggested that they are likely to "use the [Hawaiian] islands seasonally (in warm-water periods)." In June 2003, Baird et al. (2003) recorded one sighting of striped dolphins off of Niihau, in approximately 2,800 m depth, with a mean group size of 45. Barlow et al. (2004) recorded 12 sightings of striped dolphins within the Hawaiian EEZ, between August and November, with a mean group size of 12.8 individuals (Figure 6.5). Three of these sightings occurred within the Monument boundaries (Barlow et al., 2004).

Spinner Dolphin (*Stenella longirostris*)

Four subspecies of spinner dolphins are recognized worldwide and include *Stenella longirostris longirostris* (Hawaiian or Gray's), *S.l. orientalis* (Eastern), *S.l. centroamericana* (Central American) and *S.l. roseiventris* (Dwarf). They vary regionally in both form and color pattern. Generally, the spinner dolphin body is slender and small, reaching maximum lengths of 2.4 m and 78 kg. The melon is relatively flat and the beak is long and slender. The dorsal fin shape varies from moderately falcate to triangular. The color pattern is defined by a dark dorsal cape that does not dip low along the sides (like the spotted dolphin, a similar-looking species), lighter gray sides, and a light gray or white ventral side.

Spinner dolphins are found in all tropical and subtropical oceans between 30°N and 30°S. *Stenella longirostris longirostris* is the most widely spread subspecies and is typically found around oceanic islands in the Atlantic, Indian, western and central Pacific Oceans. Spinner dolphins associated with the islands in the Hawaiian Archipelago often use shallow inshore waters to rest and socialize during the day and move offshore at night to feed (Norris and Dohl, 1980).

Hawaiian spinner dolphins are resident throughout the Hawaiian Islands, including the NWHI (Norris and Dohl, 1980; Shallenberger, 1981; Tomich, 1986; Karczmarski, 2005). Historical reports demonstrate the presence of spinner dolphins in the NWHI at French Frigate Shoals, Pearl and Hermes Atoll and Kure Atoll (Amerson, 1971; Woodward, 1972; Amerson et al., 1974). According to Amerson et al. (1974), prior to 1968 there had been no reported sightings of spinner dolphin at Pearl and Hermes Atoll. Photo-identification research (2006-2008) indicates the presence of a resident population at Pearl and Hermes Atoll (NMFS, unpublished data). Shallenberger (1981) recorded sightings at Laysan, Lisianski and Maro Reef. However, photo-identification and behavioral research at Midway Atoll (1998-2001) demonstrated that a resident population of spinner dolphins was present, but the population size changed from 1998 (n= 260 individuals) to 2001 (n=140 individuals) due to the immigration of individuals to Kure Atoll (Rickards et al., 2001; Karczmarski et al., 2005). During the

2002 (August – November) Hawaiian EEZ survey, eight sightings of spinner dolphins were recorded; three of these sightings were within the Monument boundaries (Barlow et al., 2004; Figure 6.6). During the 2007 (March-April) NWHI survey, two groups of spinner dolphins were observed at Gardener Pinnacles (NMFS, unpublished data). Genetic data from spinner dolphins in the MHI suggest that limited genetic exchange is occurring from one island to the next (Andrews et al., 2006; Baird et al., 2005a; Galver, 2002). Andrews et al. (2006) also found that the spinner dolphin populations in the NWHI (Midway, Pearl and Hermes and Kure) are genetically homogenous and distinct.

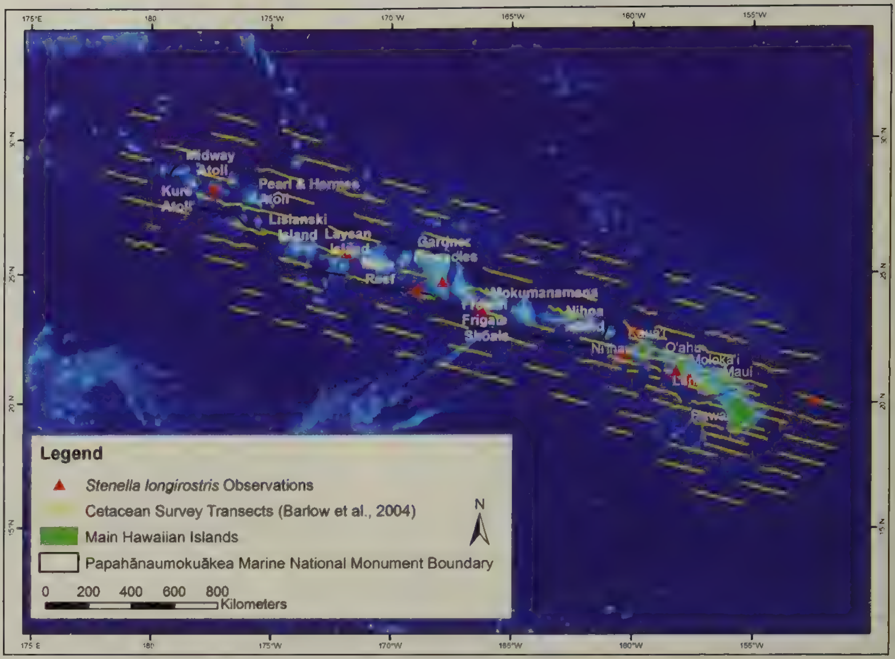


Figure 6.6. Spinner dolphin observations in Hawaiian Island EEZ. Sources: Barlow et al., 2004; Johnston et al., 2007; NFMS, unpublished; map: K. Keller.

Rough-toothed Dolphin (*Steno bredanensis*)

The rough-toothed dolphin has a moderately robust body shape; it reaches a maximum length of 2.7 m and a maximum weight of 160 kg. The dorsal fin is tall, moderately falcate and located at mid-back. The pectoral flippers are relatively large. The head is small and lacks a crease between the melon and the long beak. The color pattern is muted but defined by a dark dorsal cape, lighter gray sides and a white belly. Most rough-toothed dolphins have a mottled appearance from dark spotting on the sides, throat and belly. White scarring (from cookie cutter shark bites or other rough-toothed dolphins) is typical. The upper surface of the beak is dark and the lips and ventral surface are white.

Rough-toothed dolphins occur in deep warm temperate and tropical waters worldwide, between 45°N and 35°S.

Rough-toothed dolphins are observed in deep water around all of the MHI (Shallenberger, 1981; Tomich, 1986; Figure 6.7). Research conducted between 2000 and 2006 in the MHI (Baird et al., in press b) demonstrated that rough-toothed dolphins use the area year-round and are most commonly found in waters greater than 1,500 m deep.`Within the waters of the NWHI, Shallenberger (1981) noted sightings of rough-toothed dolphins as far north as Mokumanamana. Nitta and Henderson (1993) reported a sighting at French Frigate Shoals. During the 2002 (August – November) Hawaiian EEZ survey, 19 groups of rough-toothed dolphins were observed ranging in size from two to 15 individuals; three of these sightings were within the Monument boundaries (Barlow et al., 2004). During the 2007

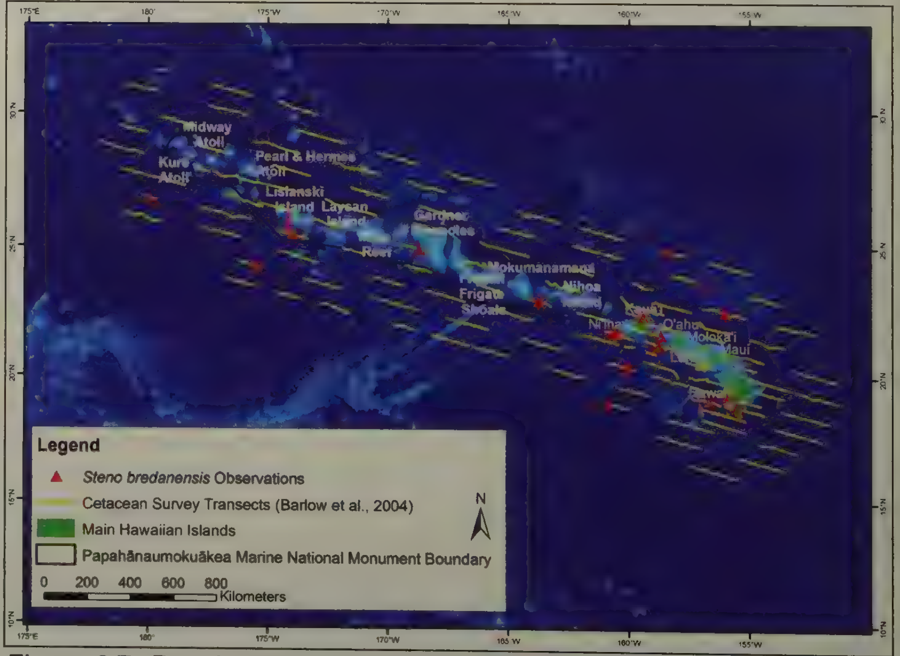


Figure 6.7. Rough-toothed dolphin observations in Hawaiian Island EEZ Sources: Barlow et al., 2004; Johnston et al., 2007; NFMS, unpublished; map: K. Keller.

(March-April) NWHI survey, one group of rough-toothed dolphins was observed near Lisianski Island (NMFS, unpublished data).

Bottlenose Dolphin (*Tursiops truncatus*)

The bottlenose dolphin is characterized by coastal and offshore ecotypes that are morphologically distinct, in which the offshore animals tend to be larger in size. In general, the bottlenose dolphin has a wide head and robust body that reaches a length of 2.5 m to 3.8 m and a maximum weight of 500 kg. Males are typically larger than females. The beak is short, and there is a distinct crease where it meets the melon. The pectoral flippers are long, and the dorsal fin is moderately tall and falcate. The color pattern ranges from a dark gray dorsal cape to lighter gray sides but lacks a distinct demarcation. The belly tends to be off-white or pinkish.

The bottlenose dolphin occurs worldwide in tropical and temperate waters within the range of 45°N and 45°S. Coastal populations are found along continents and around most oceanic islands, where they move into or reside in bays, estuaries and lower bodies of rivers. Pelagic, or offshore populations tend to reside far offshore as in the Gulf Stream of the North Atlantic and the eastern tropical Pacific.

Bottlenose dolphins are distributed throughout the Hawaiian Archipelago and occur regularly in the waters surrounding the MHI (Shallenberger, 1981; Tomich, 1986). Research within the MHI suggests that individuals are resident to particular islands, not mixing between islands (Baird et al., 2003; Baird et al., 2006; Baird et al., in press a). Sightings of dolphins in the MHI occurred in average depths of 222 m (Baird et al., 2003). Baird et al. (2006) demonstrated that off Kauai and Niihau there are two existing populations of bottlenose dolphins that are distinguished by depth preference, however, they are not reproductively isolated as individuals move between the two populations. Historical reports demonstrate the presence of bottlenose dolphins in the NWHI at Laysan Island, French Frigate Shoals, Kure Atoll, and Pearl and Hermes Atoll (Rice, 1960; Amerson, 1971; Woodward, 1972; Amerson et al., 1974). During the 2002 (August – November) Hawaiian EEZ survey, 14 groups of bottlenose dolphins were observed and ranged in size from 4 to 28 individuals; one of these sightings was within Monument boundaries, southeast of Midway Atoll (Barlow et al., 2004; Figure 6.8). During the 2007 (March-April) NWHI survey, three groups of bottlenose dolphins were observed near Nihoa, Mokumanamana and Laysan Islands (NMFS, unpublished data).

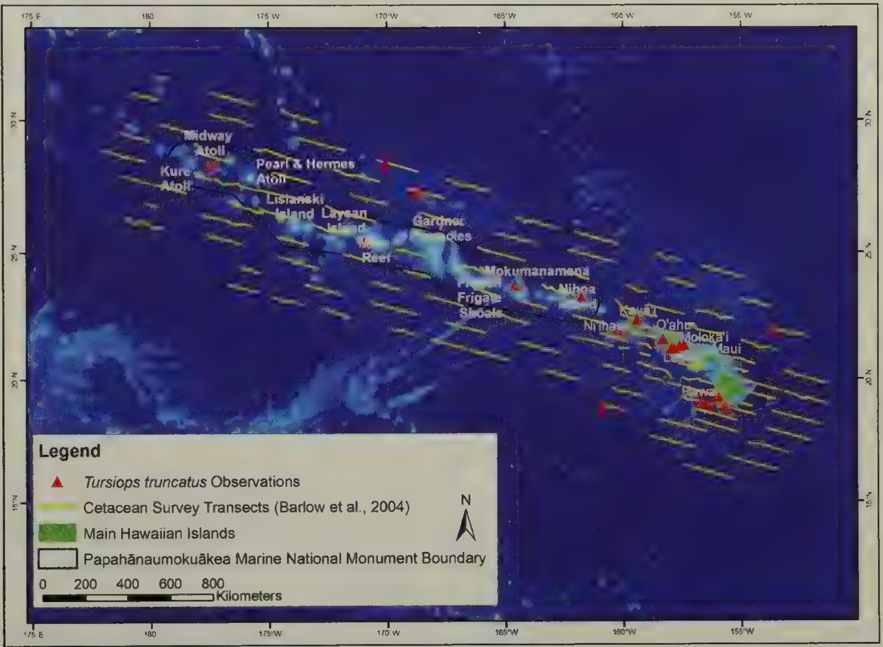


Figure 6.8. Bottlenose dolphin observations in the Hawaiian Island EEZ Sources: Barlow et al., 2004; Johnston et al., 2007; NMFS, unpublished; map: K. Keller.

Risso's Dolphin (*Grampus griseus*)

The Risso's dolphin has a bulbous, beakless head with a distinguishable longitudinal crease along the center of the melon. It has a robust body that tapers to a narrow tailstock and reaches a length of 2.6 m to 4 m and a weight of 300 to 500 kg. The dorsal fin is tall, erect and moderately falcate; and the pectoral fins are long and sickle-shaped. The color pattern can be variable from black, dark gray, brown or white and typically lightens as an individual ages. Most adults are heavily scarred with teeth rakes of other dolphins, cookie cutter shark bites and circular marks from their prey (e.g., squid).

Risso's dolphins are extensively distributed throughout tropical and warm temperate waters. They are generally found in offshore waters deeper than 1,000 m and with surface temperatures of 10 to 28°C. Although migration patterns are unknown, seasonal shifts in population density are recognized and presumed to be related to changes in water temperature and prey (e.g., squid) abundance.

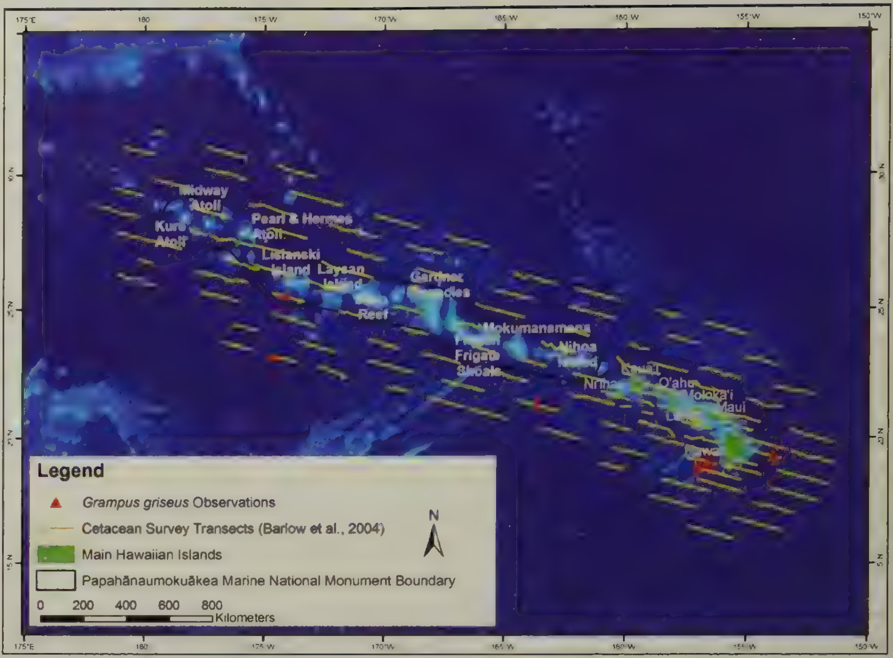


Figure 6.9. Risso's dolphin observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Sightings of Risso's dolphins are rare in Hawaiian waters (Shallenberger, 1981; Tomich, 1986). During a series of aerial surveys (in 1993, 1995 and 1998) in the MHI only two individuals were seen (Mobley et al., 2000), however, these surveys only covered waters within 46 km (25 nm) of the coast. Stranding records from five events also demonstrate the presence of Risso's dolphins within the MHI (Nitta, 1991; Maldini, 2005). During the 2002 (August-November) Hawaiian EEZ survey, seven groups of Risso's dolphins were observed (Figure 6.9). In five of these sightings, other cetacean species were present and included short-finned pilot whales, bottlenose dolphins, sei or Bryde's whales, and unidentified small dolphins (Barlow et al., 2004). In October 2002, a group of eight individuals was seen south of Lisianski Island (Barlow et al., 2004).

Fraser's Dolphin (*Lagenodelphis hosei*)

The Fraser's dolphin has a stocky body and grows to a maximum length of 2.7 m and a maximum weight of 210 kg. It has small appendages and a small, well-defined beak. The dorsal fin is triangular to slightly falcate and is more erect in males than females. The color pattern is characterized by a dark, grayish-blue dorsal cape; lighter gray sides; a whitish belly; a distinctive dark stripe on each side that runs from the eye to the anus; and a dark flipper stripe that merges with the side stripe along the lower jaw.

The Fraser's dolphin is a pantropical species that is generally found between 30°N and 30°S. It is primarily an oceanic species and found in waters deeper than 1,000 m, however, it has also been found in areas where deep water approaches the coast.

The first documentation of Fraser's dolphins in Hawaiian waters occurred during the 2002 Hawaiian EEZ survey (Barlow et al., 2004; Figure 6.10). Two groups, comprised of 47 and 171 individuals, were observed within the Hawaiian EEZ (outside of Monument waters) in November (Barlow et al., 2004).

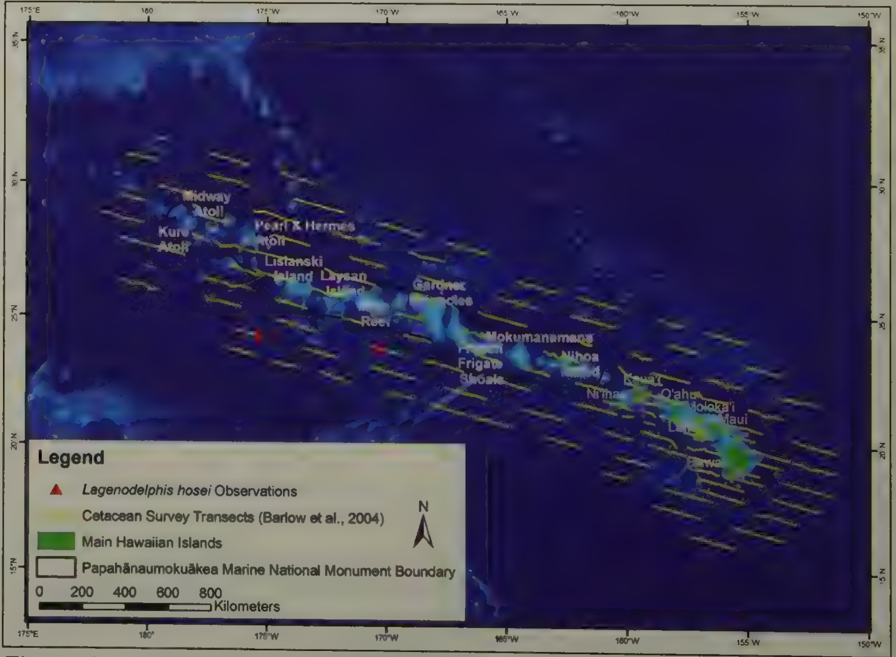


Figure 6.10. Fraser's dolphin observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Melon-headed Whale (*Peponocephala electra*)

The melon-headed whale has a moderately robust body that tapers at both ends. This whale can reach a length of 2.7 m and a weight of 275 kg. The head is narrow, triangular shaped, and has no beak. The dorsal fin is tall (as much as 30 cm), falcate and positioned at mid back. The general color pattern has an overall gray or black appearance with variable lighter gray ventral markings and white lips. The face has a dark mask over the eyes, which helps to distinguish this species from others that are similar looking (e.g., pygmy killer and false killer whales).

The melon-headed whale is a pantropical species that is found in deep waters between 40°N and 35°S.

Melon-headed whales have been observed somewhat regularly in the waters surrounding the MHI (Shallenberger, 1981; Mobley et al., 2000; Baird et al., 2003; Baird et al., 2005a). The first record is from Hilo Bay in 1841 when a group of 60 animals were driven ashore by natives (Tomich, 1986). Shallenberger (1981) noted that a group of 75-150 melon-headed whales was seen regularly off the Kohala coast of Hawaii. During 12 aerial surveys (within 46 km from the coast of the MHI) in 1993-1998, Mobley et al. (2000) observed three groups with an average of 13.5 individuals per group. Between 2000 and 2005, Baird et al. (2005a) observed 18 groups with an average of 305 individuals per group (in the MHI). Three sightings within 2003 were in an average water depth of 1,100 m (Baird et al., 2003). During the 2002 (August-November) Hawaiian EEZ survey, Barlow et al. (2004) observed one group of 171 melon-headed whales within the northwestern portion of the EEZ (outside of Monument waters; Figure 6.11).

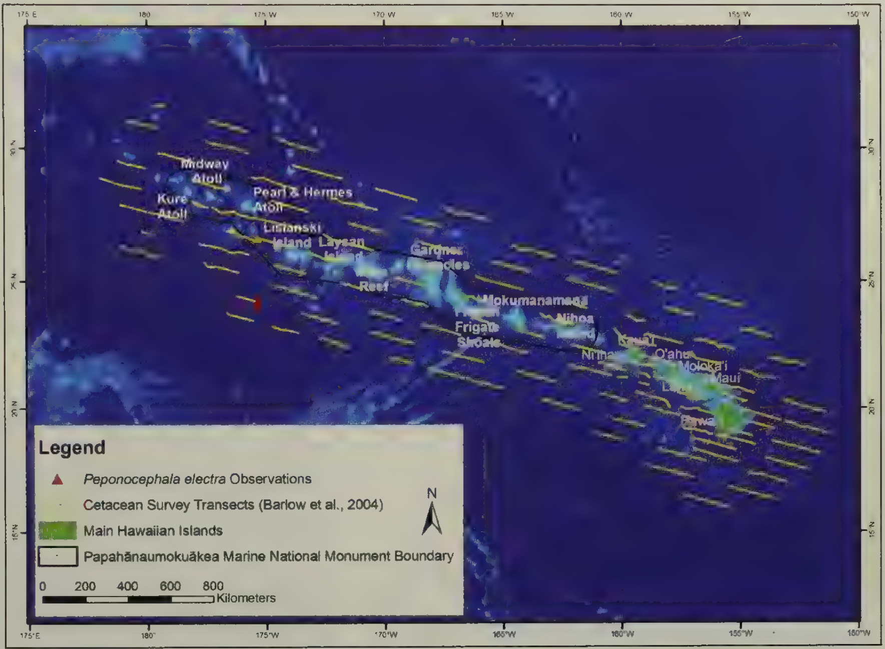


Figure 6.11. Melon-headed whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Pygmy Killer Whale (*Feresa attenuata*)

The pygmy killer whale has a moderately robust body that tapers more toward the back half. It grows to a length of 2.6 m and a weight of 170 kg. The head is rounded with no beak. The dorsal fin is tall, falcate and positioned slightly behind the mid back. The color pattern is mostly dark gray to black with white markings on the lips and belly. Areas of lighter gray extend along the sides from the eye to the anus.

The pygmy killer whale is a pantropical species that is found between 40°N and 35°S. It is one of the most poorly known species of odontocetes.

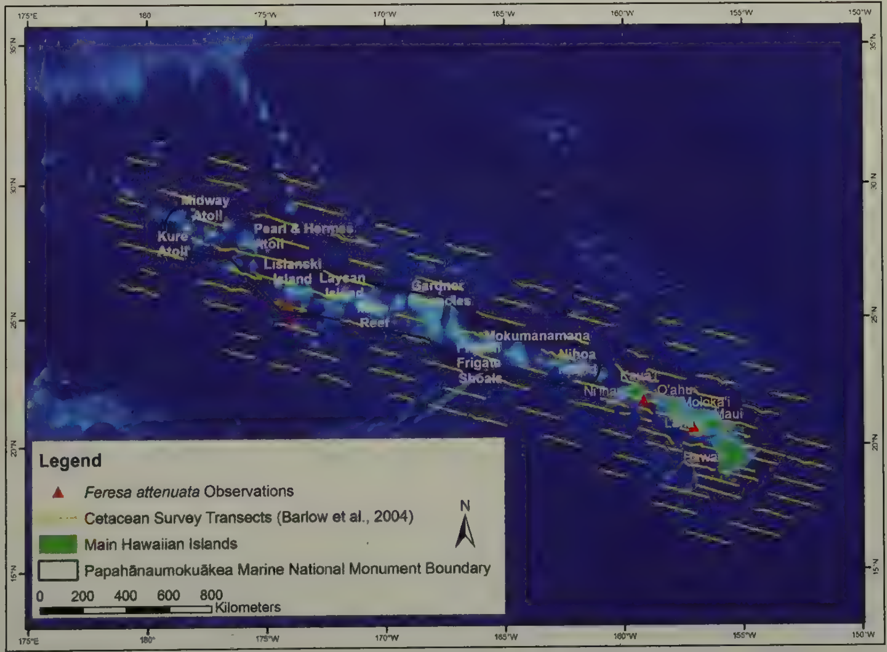


Figure 6.12. Pygmy killer whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Pygmy killer whales have been observed off the leeward coasts of Oahu and Hawaii on numerous occasions in groups as large as 100 individuals, but typically in groups smaller than 50 individuals (Shallenberger, 1981; Tomich, 1986). Between 2000 and 2005, six groups of pygmy killer whales with an average group size of 11.5 individuals were observed in the MHI (Baird et al., 2005a). Baird et al. (2003) observed one group of 13 individuals off of Kauai/Niihau in 613 m depth. A long-term study of opportunistic sightings of pygmy killer whales suggests that a small population of year-round residents is located off the island of Hawaii (McSweeney et al., in press) Barlow et al. (2004) observed three groups of pygmy killer whales within the Hawaiian EEZ (Figure 6.12). One group of five individuals was seen within the Monument boundaries near Midway Atoll (Barlow et al., 2004).

False Killer Whale (*Pseudorca crassidens*)

The false killer whale has a relatively slender body that grows to a length 6 m and a weight of 2,000 kg. The head is small and conical with the melon overhanging the tip of the lower jaw. The dorsal fin is moderately tall, falcate and positioned at mid back. The flippers are broad at the base, narrow at the tip and have a bulge in the middle of the leading edge that is a distinguishing feature. The color pattern appears dark gray to black over the entire body with lighter gray patches on the throat and chest.

False killer whales are distributed throughout all tropical and warm-temperate waters, generally occurring between 50°N and 50°S. They are typically found in waters deeper than 1,000 m.

Two populations of false killer whales are recognized within the Hawaiian EEZ (Chivers et al., 2007). Genetic and photographic evidence demonstrate the presence of an offshore population closely related to animals found in the eastern North Pacific (and Palmyra Atoll), and an inshore population that is demographically distinct (Chivers et al., 2007; Baird et al., 2008). Both populations are listed as one strategic stock under the amendments to the MMPA as a result of interactions with Hawaii longline fisheries (http://www.nmfs.noaa.gov/pr/species/esa/mammals.htm). According to Baird et al. (2008), false killer whales are observed infrequently in the nearshore waters of the MHI. Between 1986 and 2006, only 50 groups of false killer whales were encountered (Baird et al., 2008). During aerial surveys within 46 km of the coastline (1993-1998) Mobley et al. (2000) observed 21 groups. Baird et al. (2008) encountered false killer whales in depths between 48 m and 4,331 m depth. During the 2002 survey, Barlow et al. (2004) observed two groups of two and 19 individuals within the northwestern portion of the Hawaiian EEZ in August and September 2002, respectively (Figure 6.13). During the 2007 NWHI survey, one group of false killer whales was observed near Lisianski Island (NMFS, unpublished data).

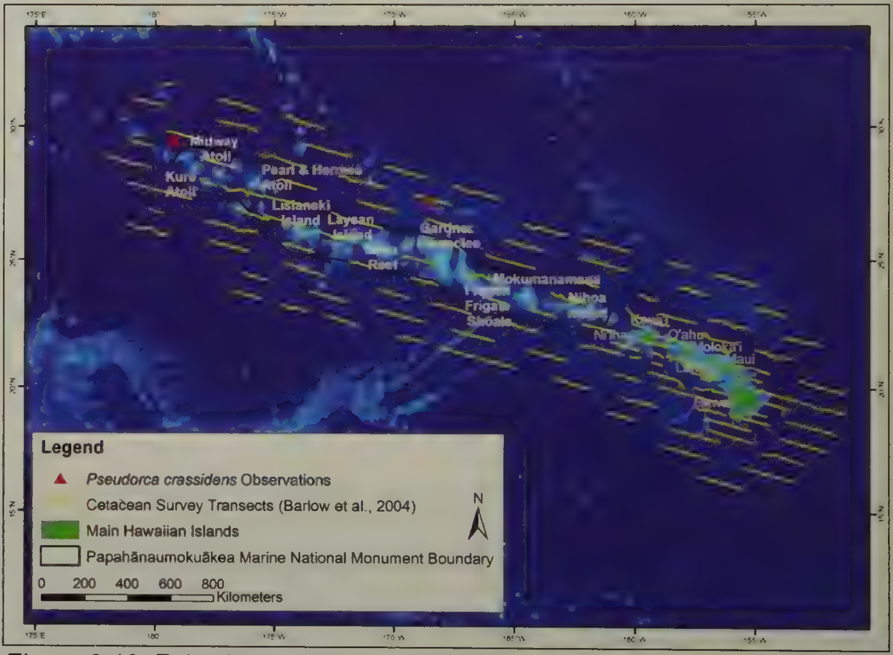


Figure 6.13. False killer whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Short-finned Pilot Whale (*Globicephala macrorhynchus*)

The short-finned pilot whale has a large, bulbous head in which the melon protrudes beyond the mouthline. The beak is very short and the mouthline is noticeably upturned toward the eye. The dorsal fin is falcate, set forward of the midbody, broad at the base and long relative to its height. Males have distinctly broader dorsal fins than females. The species is relatively large with females reaching lengths of 5.5 m and weights of 1,000 kg and males reaching lengths of 6.1 m and weights of 3,000 kg. The color pattern is generally black or dark brown with a light gray throat patch, saddle behind the dorsal fin and streak behind the eye.

The short-finned pilot whale is a tropical to warm-temperate species found between 50°N and 40°S. They typically occur in deep water.

Short-finned pilot whales are seen throughout the year in the MHI (Shallenberger ,1981; Mobley et al., 2000; Baird et al., 2003). Shallenberger (1981) noted that group sizes were often greater than 100 individuals and rarely smaller than 30 individuals. Aerial surveys conducted within 46 km of the coastline within the MHI (1993-1998) resulted in 73 observed groups of pilot whales with an average group size of 8.4 individuals (Mobley et al., 2000). A summary of sighting data from 2000 to 2005 resulted in 80 observed groups of pilot whales with an average of 20 individuals per group (Baird et al., 2005a). Data from May and June of 2003 demonstrated that the average depth of sighting locations for 17 groups of pilot whales within the MHI was 1,142 m (Baird et al., 2003). During the 2002 survey of the Hawaiian EEZ, Barlow et al. (2004) observed 25 groups of pilot whales, ranging in size from 2 to 28 individuals (Figure 6.14). Four sightings were within the Monument boundaries (Barlow et al., 2004). During the 2007 (March-April) NWHI survey, four groups of pilot whales were observed within the Monument between Pearl and Hermes Atoll and Midway Atoll, near French Frigate Shoals and at Gardener Pinnacles (NMFS, unpublished data).

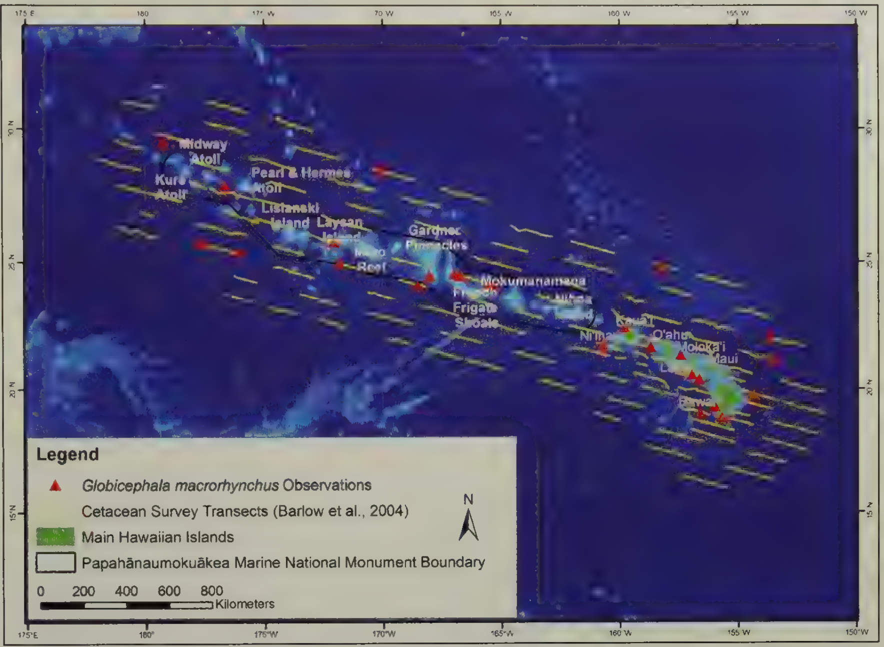


Figure 6.14. Short-finned pilot whale observations in the Hawaiian Island EEZ. Sources: Barlow et al., 2004; Johnston et al., 2007; NFMS unpublished; map: K. Keller.

Killer Whale (*Orcinus orca*)

The killer whale has a stocky body with a conical shaped head that lacks a prominent beak. This is the largest of the delphinid species with females growing to a maximum length of 8.0 m and an average weight of 3,000 kg and males growing to a maximum length of 9.0 m and an average weight of 6,000 kg. The dorsal fin is large, ranging in size from 0.9 m for females to 1.8 m for males. The shape of the dorsal fin is variable, from falcate in females and juveniles to tall and erect in males. The color pattern of the killer whale is its most distinctive feature. The dorsal side of the body is black, as are the pectoral flippers. The ventral side of the body is white and lobes extend from the belly along each side behind the dorsal fin. Distinct white patches are located slightly above and behind the eyes. A gray to white shaded saddle is located on the back behind the dorsal fin.

Killer whales are considered the most widespread cetacean. They can be found in any marine region but are more abundant in cool temperate regions. In the Pacific Northwest, two different groups of killer whales have been identified. Both the "transients" and "residents" are present year-round, however the "transients" have larger home ranges and prey on marine mammals, while resident pods target fish as their primary prey. Whether this pattern is universal is unknown. Movements of killer whales appear to be driven by food availability (American Cetacean Society, 1995 -2007).

Although infrequent, sightings of killer whales have been documented in the Hawaiian EEZ (Shallenberger, 1981; Tomich, 1986; Baird et al., 2005b). Baird et al. (2005b) reported 21 records of killer whale sightings within the Hawaiian EEZ between 1994 and 2004. During an aerial survey in March of 2000, Mobley et al. (2001) observed a group of killer whales west of Niihau. In May of 2003, Baird et al. (2003) observed one group of four individuals off the west side of the island of Hawaii in 773 m depth. Barlow et al. (2004) observed two groups of killer whales, each consisting of two individuals, in September and November of 2002 (Figure 6.15). The November sighting occurred just north of French Frigate Shoals (Barlow et al., 2004).

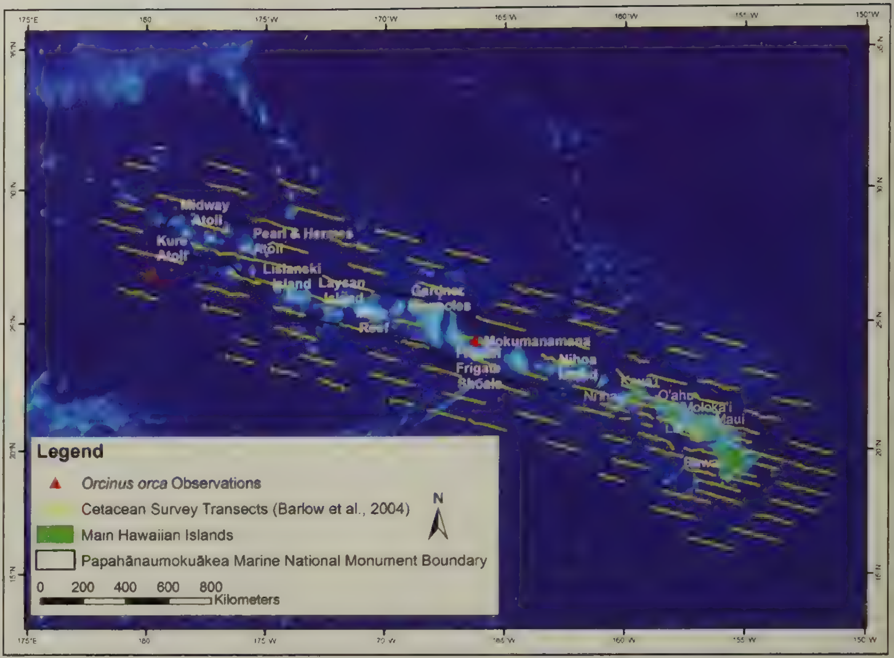


Figure 6.15. Killer whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Sperm Whale (*Physeter macrocephalus*)

The sperm whale is large and distinctive, with a huge square head comprising approximately one-third of its total length. Adult females can reach 12 m in length and 24,000 kg in weight. Adult males are larger, reaching 18 m and weighing up to 57,000 kg. The blowhole is set at the front of the head and skewed to the left. The dorsal fin is small and rounded. The skin behind the head is wrinkled. The color pattern is black to brownish-gray with white around the mouth and belly.

Sperm whales are cosmopolitan in their distribution and inhabit waters from the equator to the edge of the polar ice packs. Only adult male sperm whales will move between higher and lower latitudes, while females, calves and juveniles are generally found in more topical and subtropical waters year around. The breeding grounds are located in the tropical and subtropical waters of the lower latitudes. Sperm whales are primarily found in waters greater than 600 m deep.

Data from the Townsend (1935) charts indicate that occurrences of sperm whales around the Hawaiian archipelago were common (Figure 6.16). The whaling industry decimated their numbers, and currently the species is listed as Endangered under the ESA (http://www.nmfs.noaa.gov/pr/species/esa/mammals.htm). Shallenberger (1981) reported occasional sightings and stranding events within the MHI. Sperm whales were the most frequently observed species within the Hawaiian EEZ between August and December 2002 (Barlow et al., 2004). Barlow et al. (2004) observed 46 groups ranging in size from one to six individuals. Twelve of these sightings were within the Monument boundaries (Barlow et al., 2004).

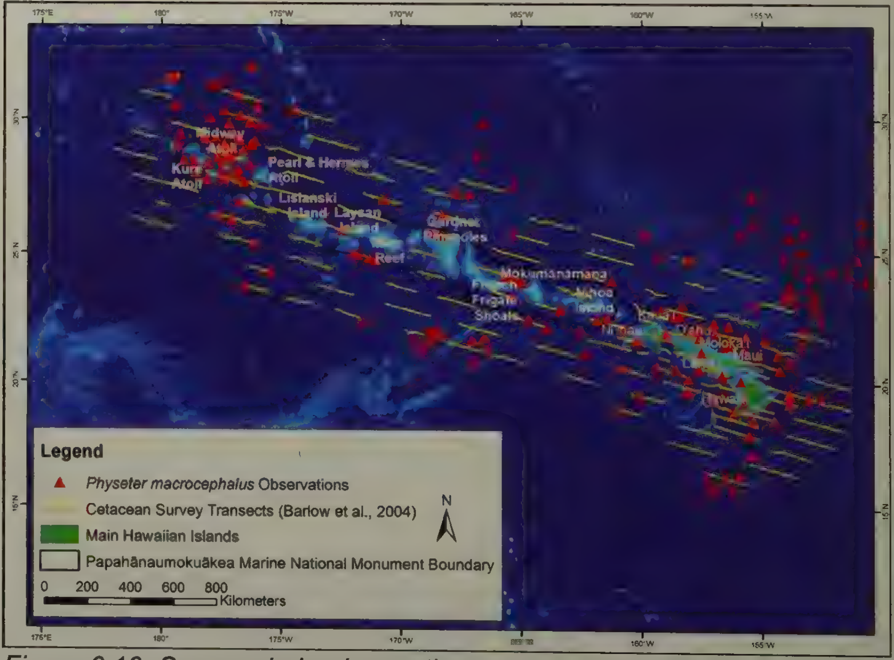


Figure 6.16. Sperm whale observations around the Hawaiian archipelago Sources: Barlow et al., 2004; Johnston et al., 2007; NFMS, unpublished; Townsend, 1935; map: K. Keller.

During the 2007 (March-April) NWHI survey, seven groups of sperm whales were observed within the Monument (NMFS, unpublished data).

Pygmy Sperm Whale (*Kogia breviceps*)

The pygmy sperm whale has a small, robust body with a bulbous, square-shaped head with a pointed snout, a narrow mouth and undershot lower jaw. It ranges from 2.8 m to 3.5 m in length and reaches a maximum weight of 450 kg. The blowhole is set far back on the head and offset to the left. The dorsal fin is small, falcate and located behind the midpoint of the body. The pectoral flippers are small and located unusually close to the head. Coloration ranges from a dark gray on the back to pinkish-white on the belly, and there are half-moon shaped markings between the eye and the flipper, sometimes referred to as "false-gills". The pygmy sperm whale closely resembles the dwarf sperm whale.

The pygmy sperm whale occurs in tropical to temperate regions worldwide and is generally found in deep waters seaward of the continental shelf. Pygmy sperm whales are thought to be non-migratory and are generally found singly or in small groups up to five individuals.

Pygmy sperm whales are observed occasionally within Hawaiian waters. Shallenberger (1981) combines the two *Kogia* species into one section because of the possible misidentification of each species. Most data come from strandings in the MHI, which have occurred on Kauai, Oahu, Molokai and Maui (Shallenberger, 1981). In June 2003, Baird et al. (2003) observed one group of two individuals between Kauai and Niihau in 700 m depth. Two lone individuals were observed within the northwestern portion of the Hawaiian EEZ by Barlow et al. (2004; Figure 6.17) in November 2002. Within the Monument there is a single record, from 1923, of a beach cast skeleton that was identified as a pygmy sperm whale (Amerson, 1971). It was this event that led to the naming of Whale Island at French Frigate Shoals (Amerson, 1971).

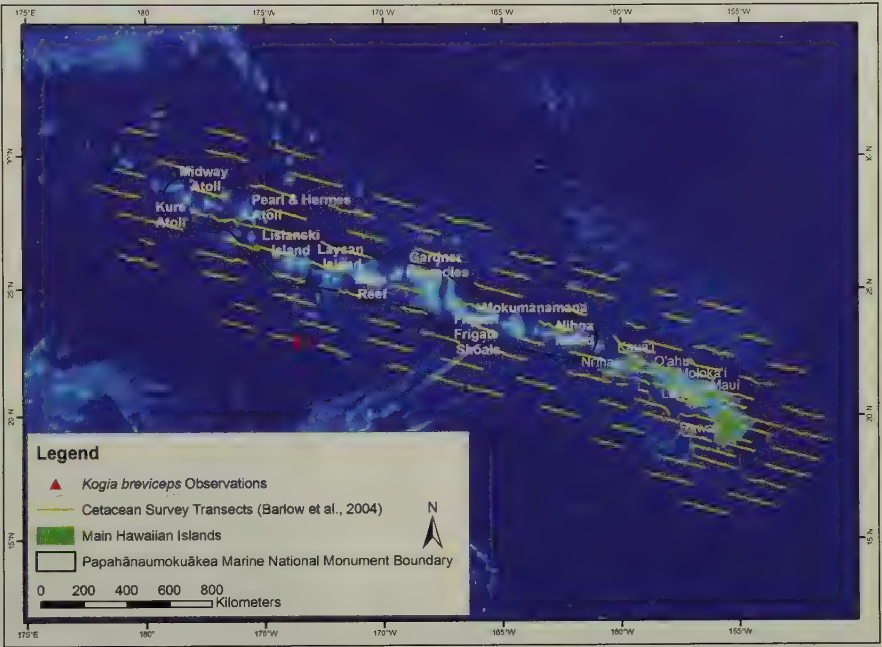


Figure 6.17. Pygmy sperm whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Dwarf Sperm Whale (*Kogia sima*)

The dwarf sperm whale is nearly identical in appearance to the pygmy sperm whale; however, the dwarf sperm whale has a dorsal fin that is more prominent and positioned further forward on its back. Additionally, the dwarf sperm whale is a smaller whale, reaching a length of 2.7 m and weighing approximately 275 kg.

The dwarf sperm whale is a tropical and temperate species, generally found in offshore waters, but somewhat more coastal than the pygmy sperm whale. There is no evidence to suggest that the dwarf sperm whale migrates.

Shallenberger (1981) combines the two *Kogia* species into one section because of the possible misidentification of each species. Stranding events have been recorded on Oahu and Hawaii (Tomich, 1986). In May and June of 2003, Baird et al. (2003) encountered eight groups of dwarf sperm whales near Lanai, Kauai and Niihau. The average group size was two individuals, and they were observed in waters with an average depth of

2,004 m (Baird et al., 2003). Barlow et al. (2004) observed dwarf sperm whales on five occasions within the Hawaiian EEZ in October and November 2002 (Figure 6.18). The species was observed singly or in groups of up to three individuals (Barlow et al., 2004).

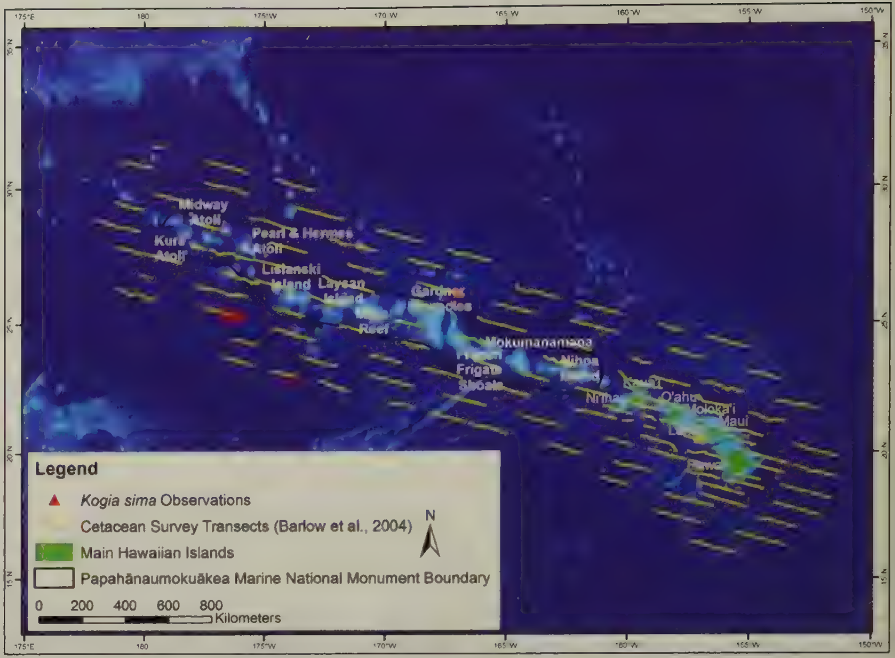


Figure 6.18. Dwarf sperm whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Blainville's Beaked Whale (*Mesoplodon densirostris*)

The Blainville's beaked whale, sometimes called the dense-beaked whale, has a robust body that is compressed laterally. It is a medium-sized whale that reaches 5.8 m in length and 3,500 kg in weight. The dorsal fin is small, falcate and positioned approximately two-thirds down the length of the body. The color pattern is silver-gray to brown on the dorsal surface with lighter gray to white on the belly. Blainville's beaked whales are typically covered with white or pale-gray circular marks or scars that are likely caused by cookie cutter sharks. They have a distinct mouthline that sweeps up at the middle of the lower jaw. Males have a tooth protruding from each side of the lower jaw at this site.

Blainville's beaked whales are a tropical and temperate species and are considered the most widely distributed mesoplodont. They are found primarily in deep waters, 500-1,000 m. There is no evidence of seasonal movements or migrations.

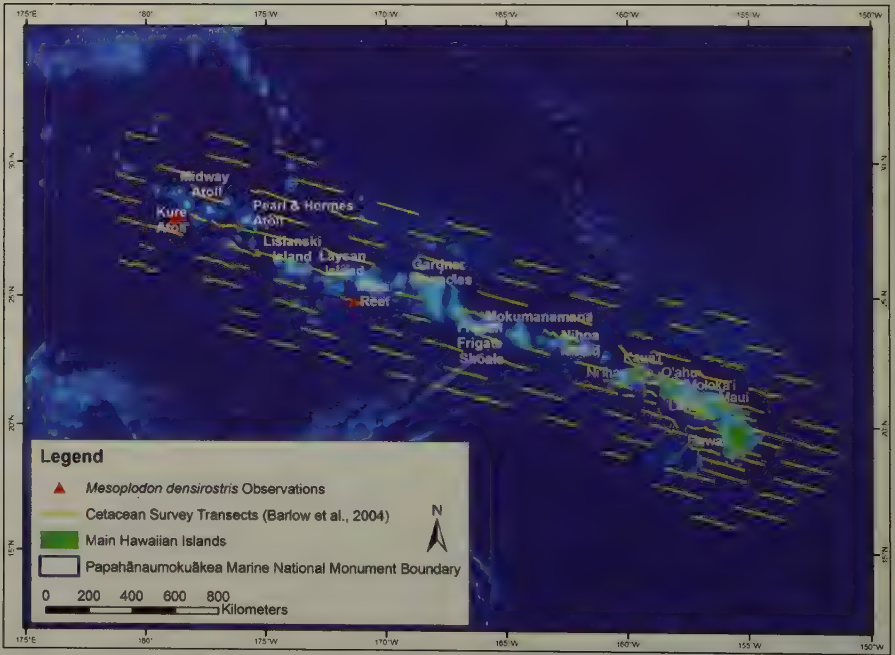


Figure 6.19. Blainville's beaked whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Blainville's beaked whales have been observed in the MHI off of Oahu, Hawaii, Kauai and Molokai (Shallenberger, 1981; Tomich, 1986; Mobley et al., 2000, Baird et al., 2003). Group sizes range from two to seven individuals (Shallenberger, 1981; Tomich, 1986; Mobley et al., 2000; Baird et al., 2003). Five groups observed by Baird et al. (2003) were in average water depths of 1,304 m. Recent satellite tagging studies off the west coast of the island of Hawaii suggest that this population of Blainville's beaked whales is island-associated and exhibits strong site fidelity (Schorr et al., In press). Within the Monument boundaries, the earliest record of Blainville's beaked whales is from a stranding event of two individuals at Midway Atoll in April 1961 (Galbreath, 1963; Shallenberger, 1981). Barlow et al. (2004) observed Blainville's beaked whales (one to two individuals per sighting) within Monument waters in September and October 2002 (Figure 6.19).

Cuvier's Beaked Whale (*Ziphius cavirostris*)

Cuvier's beaked whale has a long, stocky body. Adults range in length from 5 m to 7.5 m and weigh from 2,000 kg to 3,000 kg. The head is small, the melon is steeply tapered and the beak is short and poorly-defined. Mature males have two teeth protruding from the front of the lower jaw. The dorsal fin is small, falcate and located approximately two-thirds back along the length of the body. The color pattern varies from dark gray to light brown, with the head and neck, and eventually the body, becoming lighter in color as the whale ages. This is particularly pronounced in males. Scars from cookie cutter sharks can give a mottled appearance to the sides and belly.

Cuvier's beaked whales occur in all offshore waters except those in the polar regions. They are primarily found in waters greater than 1,000 m deep.

Cuvier's beaked whales are observed infrequently within the Hawaiian EEZ. Shallenberger (1981) noted two sightings off of Lanai and Maui. Aerial surveys of the MHI conducted during 1993, 1995 and 1998 resulted in seven observed groups of Cuvier's beaked whales with an average group size of three individuals (Mobley et al., 2000). During a 10 year period (1990-2006), McSweeney et al. (2007) encountered Cuvier's beaked whales on 35 occasions off the west coast of the island of Hawaii. Resightings of individuals during this time suggest some degree of site fidelity and the presence of a resident population. Stranding events at Midway Atoll and Pearl and Hermes Atoll demonstrate the presence of Cuvier's beaked whales within the Monument (Shallengberger, 1981). In addition, Barlow et al. (2004) observed groups within the Monument, at Gardener Pinnacles and north of Mokumanamana in August of 2002 (Figure 6.20).

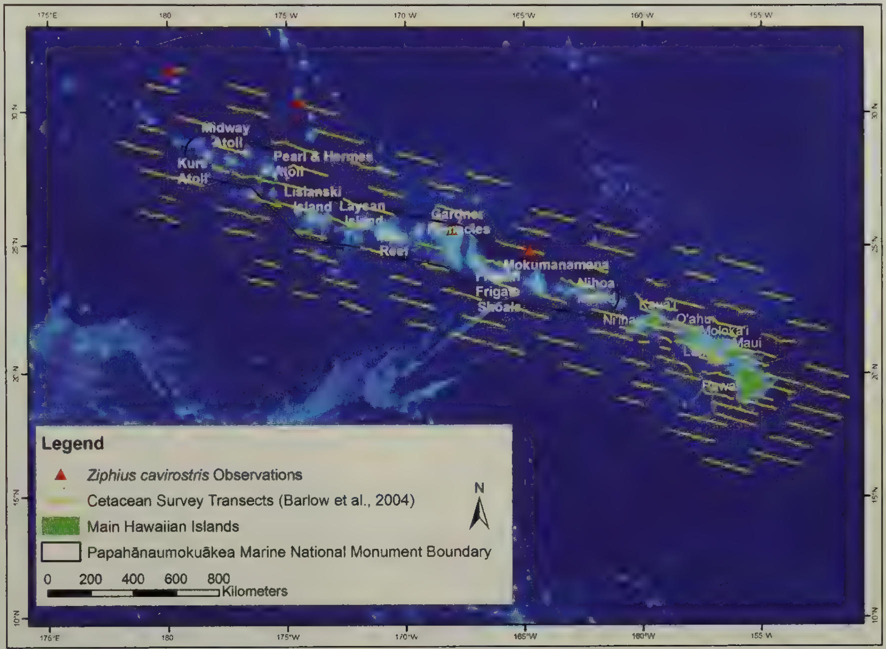


Figure 6.20. Cuvier's beaked whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Longman's Beaked Whale (*Indopacetus pacificus*)

The Longman's beaked whale, sometimes referred to as the tropical bottlenose whale, can reach 9 m in length. It has a bulbous head and moderately long beak, from which two teeth erupt in males. The dorsal fin is pointed, falcate, and located behind the midpoint of the body. The color varies from brown to bluish gray, and the head and sides can be a lighter color in younger animals. This species has been misidentified as the southern bottlenose whale.

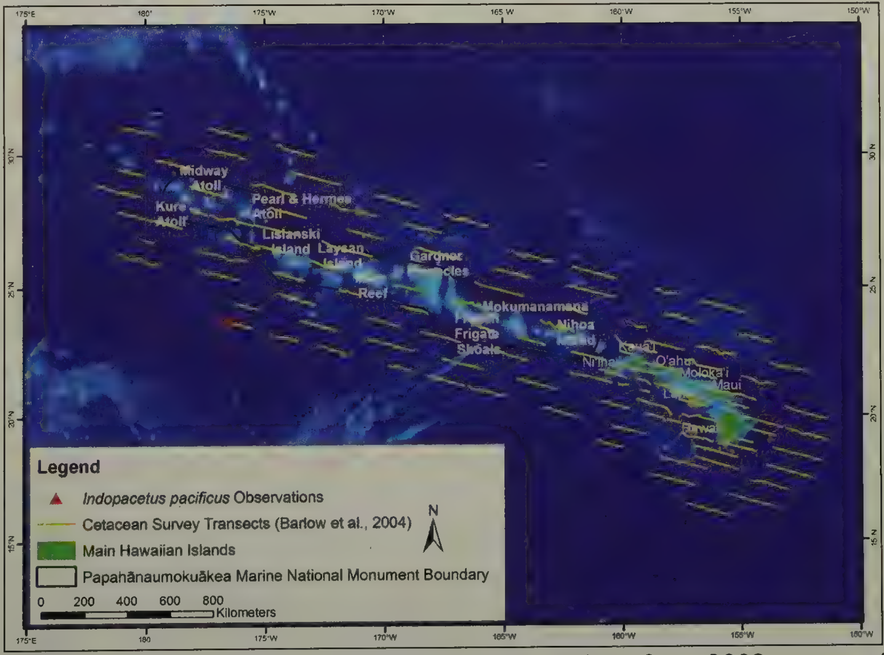


Figure 6.21. Longman's beaked whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Little is known about the range of Longman's beaked whale, but it is thought to occur primarily in pelagic waters within the Indo-Pacific region.

Longman's beaked whale is rare in Hawaiian waters. There are only two confirmed sightings within the Hawaiian EEZ. The first was made in November 2002 when Barlow et al. (2004) observed one group of four individuals within the northwestern portion of the EEZ (Figure 6.21). The second confirmed sighting was a group of 30-35 individuals off of the west coast of the island of Hawaii in 2007 (http://www.cascadiaresearch.org/robin/August2007.htm).

Minke Whale (*Balaenoptera acutorostrata*)

Minke whales are the smallest of the baleen whales. At least two subspecies of the common minke whale are recognized and include the North Pacific (*B.a.scammoni*) and North Atlantic (*B.a. acutorostrata*). The dwarf minke whale is considered a potential third subspecies but has not been given an official scientific name. The common minke whale has a small, slender body and a pointed triangular head with a well-defined longitudinal ridge along the rostrum. Adults range in length from 7 m to 10.7 m and weigh as much as 9,200 kg. Females are slightly longer than males. The falcate dorsal fin is set approximately two-thirds back along the length of the body. The color pattern is black or dark gray on the dorsal side with a lighter gray chevron across the back and white on the belly. A white band across the middle of the pectoral flippers is a distinctive characteristic of this species.

Common minke whales occur in the North Atlantic and North Pacific and migrate from the polar and temperate waters in the summer to the tropical waters in the winter. They are frequently observed in coastal or shelf waters, rather than deep offshore habitats. In the eastern Pacific, minke whales are found from the Bering Sea south to the coast of Baja California, and in the western Pacific they are found from the Sea of Okhotsk to the Sea of Japan. The winter distribution of North Pacific minke whales can be inferred from the distribution of their distinctive calls (termed "boings"). Boings are heard primarily between 15°N and 30°N in the months of November through March (Rankin and Barlow 2005). Shallenberger (1981) lists the minke whale under "animals sighted in Hawaiian waters but not considered part of the normal cetacean fauna." One minke whale was observed within the Hawaiian EEZ by Barlow et al. (2004) in November 2002 (Figure 6.22).

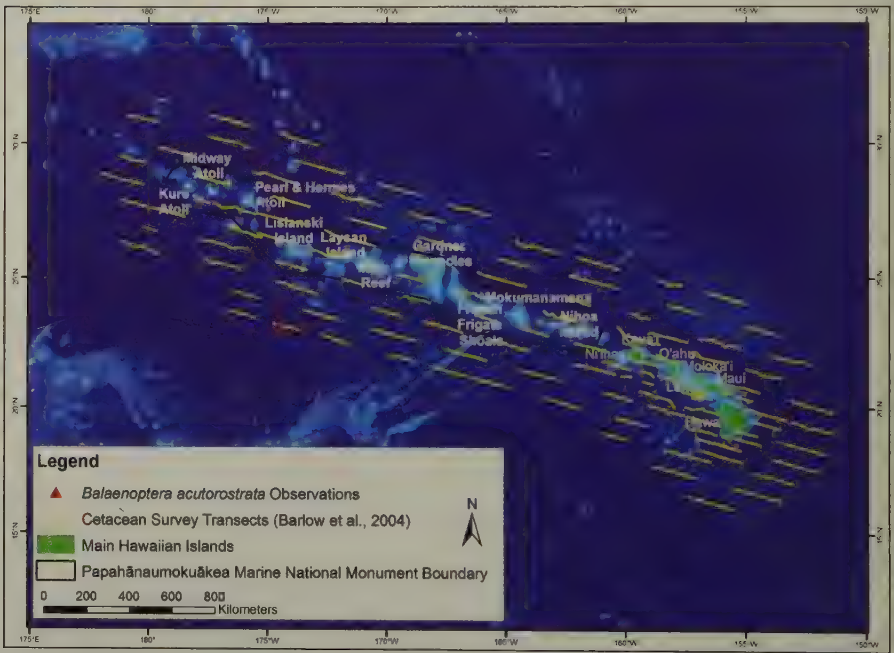


Figure 6.22. Minke whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Bryde's Whale (*Balaenoptera edeni*)

The Bryde's whale has a long, slender body with a pointed rostrum. Females are larger than males and can reach a length of 15.5 m and a weight of 40,000 kg. Three ridges extend from the blowhole to the tip of the rostrum, which is a diagnostic feature of this species. The dorsal fin is extremely falcate, tall (up to 45 cm), and positioned two-thirds of the way along the length of the body. The color pattern is gray on the dorsal side and white on the belly, sometimes with banding or chevrons.

Bryde's whales are found in tropical and subtropical waters of the Pacific, Atlantic and Indian Oceans. They are rarely seen north or south of 40°. The whales are often seen at nearshore upwellings but are also occasionally found offshore. Some evidence suggests that there are two forms of the Bryde's whale, an inshore and an offshore that may differ in reproductive cycles and diet. The Bryde's whale is not as migratory as the sei whale, but limited migration does take place in some populations (offshore form), while other populations are resident year-around (inshore form).

Shallenberger (1981) listed the Bryde's whale as a rare species in Hawaiian waters. He noted one confirmed sighting 87 km southeast of Nihoa in April of 1977 (Shallenberger, 1981). Tomich (1986) cites Leatherwood et al. (1982) as noting that Bryde's whales are "relatively abundant over shallows northwest of Hawaii and near Midway Islands." During the 2007 NWHI survey, a single Bryde's whale was observed off the east coast of Niihau (NMFS, unpublished data). During August through October of the 2002 Hawaiian EEZ survey, Barlow et al. (2004) observed 14 groups of Bryde's whales (Figure 6.23). With the exception of two sightings, in which there were two whales present, all were of single whales. Six of the sightings were within the Monument boundaries (Barlow et al., 2004).

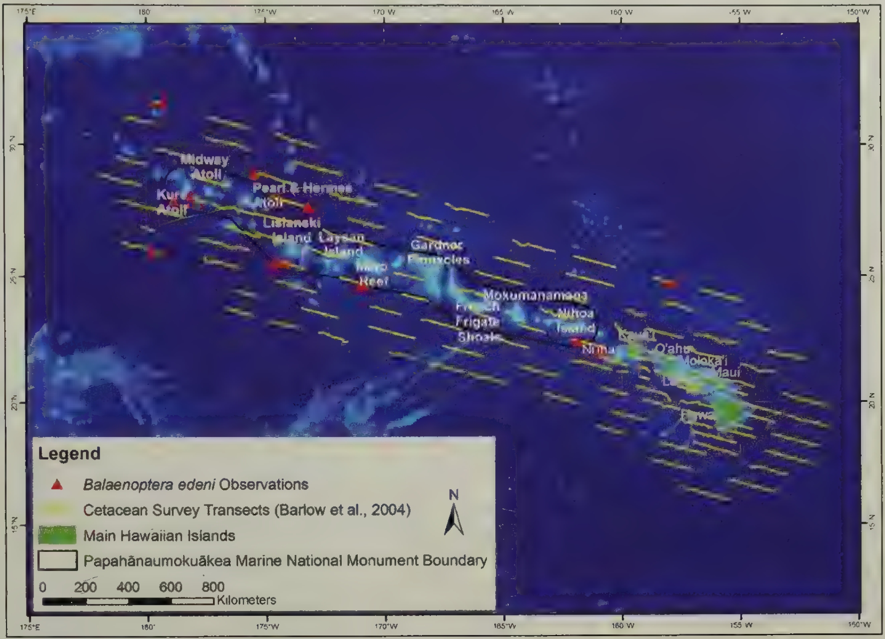


Figure 6.23. Byrde's whale observations in the Hawaiian Island EEZ. Sources: Barlow et al., 2004; Johnston et al., 2007; NMFS, unpublished; map: K. Keller.

Sei Whale (*Balaenoptera borealis*)

Sei whales are similar in appearance to Bryde's whales, with a gray dorsal and white ventral surface, and with the dorsal fin rising at a steep angle from the back. Adults reach a maximum of 20 m in length, and may weigh as much as 45,000 kg. Sei whales have only a single rostral ridge and lack the two additional parallel longitudinal ridges that are evident in the Bryde's whales.

Sei whales are found from the tropics to polar regions in the northern and southern hemispheres, but most often occur in the mid-latitude temperate zones. They are migratory open-ocean whales, not often observed near the coasts. The species is listed as Endangered under the ESA (http://www.nmfs.noaa.gov/pr/species/esa/mammals.htm).

Neither Shallenberger (1981) nor Tomich (1986) mention sei whales. Individual sei whales were observed on several occasions within the Hawaiian

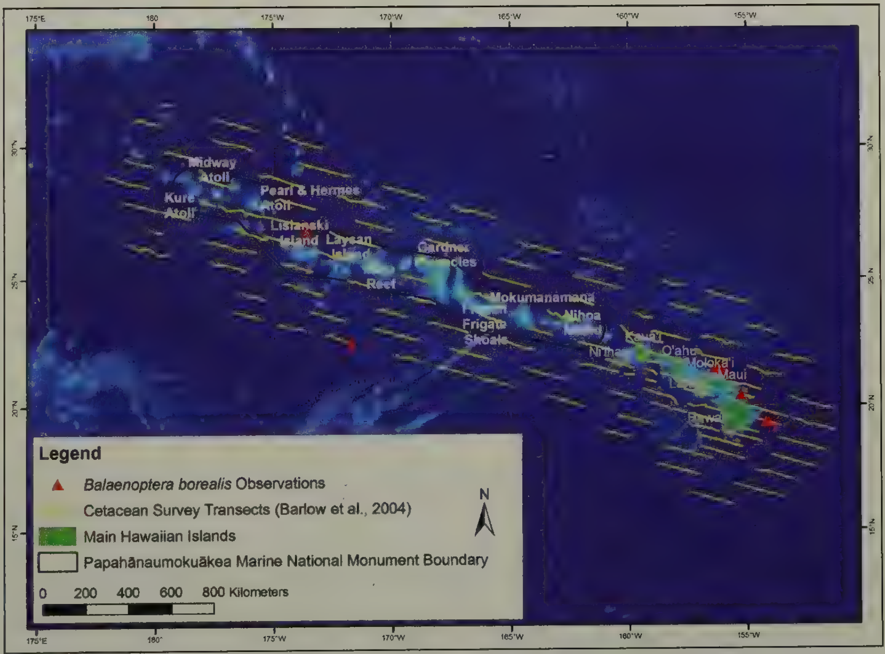


Figure 6.24. Sei whale observations in the Hawaiian Island EEZ. Sources: Barlow et al., 2004; Johnston et al., 2007; NMFS, unpublished; map: K. Keller.

EEZ (but outside of Monument waters) by Barlow et al. (2004) in November 2002 (Figure 6.24). In April 2007, during the NWHI survey a single sei whale was observed between Laysan and Lisianski Islands (NMFS, unpublished data).

Fin Whale (*Balaenoptera physalus*)

Similar to the Bryde's and sei whales, fin whales are dark brown or gray dorsally and white ventrally. Fin whales are significantly larger reaching a length of 24 m and a weight of 120,000 kg. The dorsal fin is variable and either pointed or falcate. Fin whales have a distinctive asymmetrical color pattern on the lower jaw; the right side (including baleen) is white and the left side is dark gray or black. In addition, most individuals have a v-shaped chevron across the back of the head and a swirled blaze on the right side of the head.

Fin whales are found in all oceans of the world, but primarily occur in cooler temperate regions and concentrate on shelf and in coastal waters. They can be found over a broad latitudinal range throughout the year, however, some appear to migrate, spending the summer in the northern polar region and the winter in warmer waters of lower latitudes. Like the sei whale, fin whales are listed as Endangered under the ESA (http://www.nmfs.noaa.gov/pr/species/esa/mammals.htm).

Shallenberger (1981) listed fin whales as rare in Hawaiian waters. He reported on two sightings off of Oahu and one stranding on Maui (Shallenberger, 1981). In February 1994, a single fin whale was observed near Kauai (Mobley et al. 1996). Acoustic recordings have also detected the presence of fin whales off Oahu and Midway (Thompson and Friedl, 1982; McDonald and Fox, 1999). During the period of September through November 2002, Barlow et al. (2004) observed five groups of fin whales within the Hawaiian EEZ (Figure 6.25). A single individual was observed within the Monument between Maro Reef and Laysan Island (Barlow et al., 2004).

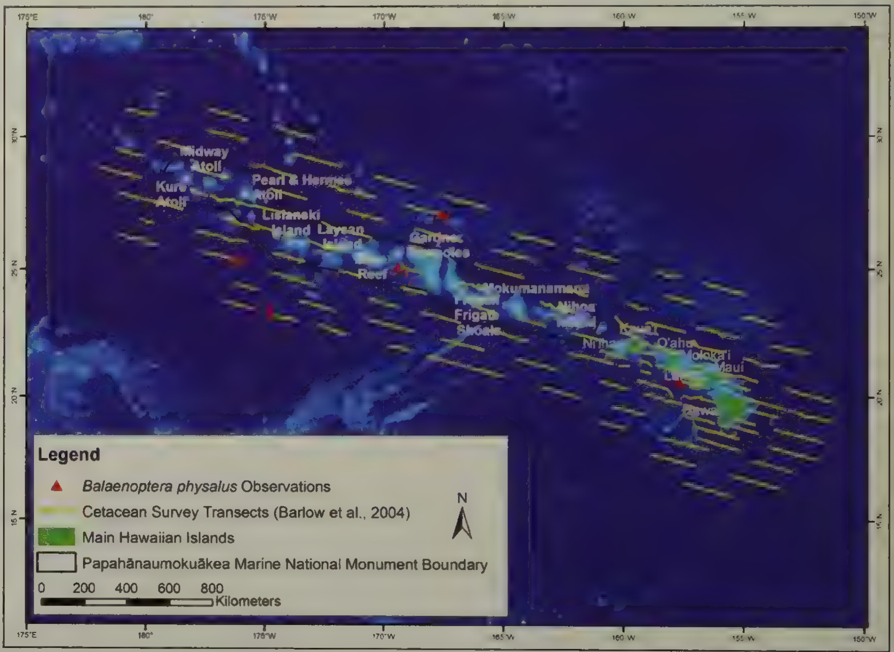


Figure 6.25. Fin whale observations from 2002 survey of the Hawaiian Island EEZ. Source: Barlow et al., 2004; map: K. Keller.

Humpback Whale (*Megaptera novaeangliae*)

The humpback whale has a large, robust body that reaches a maximum length of 17 m and a maximum weight of 40,000 kg. Females are slightly larger than males. Humbacks have very long flippers (up to one-third the length of the body). The head and lower jaw are covered in tubercles. The dorsal fin is variable from tall and falcatè to a small hump. The large flukes are concave with a serrated trailing edge. The color pattern is variable. It can be black on the dorsal side and black, white, or mottled black and white on the ventral side.

Humpback whales are found in all of the major oceans and occur primarily in coastal waters (Figure 6.26). They are a migratory species and spend the summer in the polar regions and the winter in tropical waters. Four stocks are believed to occur in the North Pacific, including one that winters in the central North Pacific and Hawaii. Multiple stocks also occur in the North Atlantic, Northern Indian Ocean and in the southern hemisphere. Humpback whales are listed as Endangered under the ESA (http://www.nmfs.noaa.gov/pr/species/esa/mammals.htm).

Humpback whales within the MHI have been extensively studied for nearly four decades (Herman and Antinoja, 1977; Shallenberger, 1977; Herman et al., 1980; Shallenberger, 1981; Calalmonkidis et al., 2008) and individ-

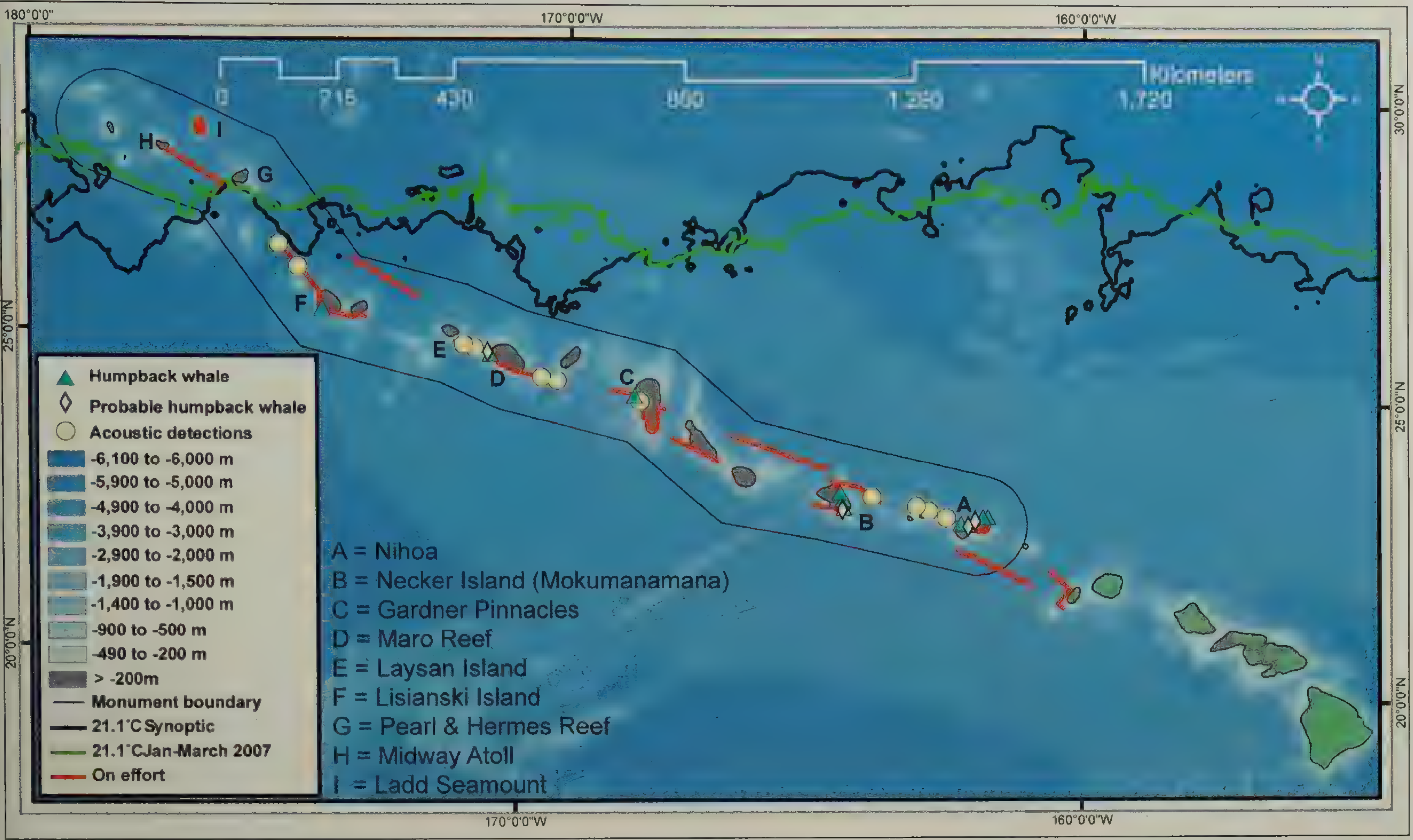


Figure 6.26. Humpback whale modeled habitat. A = Nihoa; B = Mokumanamana; C = Gardner Pinnacles; D = Maro Reef; E = Laysan Island; F = Lisianski Island; G = Pearl and Hermes Atoll; H = Midway Atoll; and I = Ladd Seamount. Map: Johnston et al., 2007.

ual whales photographed in Hawaii are also known from records in the northern feeding grounds in Alaska and British Columbia (Calambokidis et al., 2008). The whales migrate to the waters surrounding the Hawaiian Islands beginning in November and remain there until late May (Shallenberger, 1981). While in Hawaiian waters, they are found exclusively in shallow waters less than 183 m (Shallengberger, 1981; Johnston et al., 2007). Humpback whales may use the waters of the NWHI throughout the winter months, and were observed within the Monument boundaries near Nihoa, Mokumanamana, Gardner Pinnacles, Maro Reef and Lisianski Island (Johnston et al., 2007). Nine groups were observed, two of which contained calves (Johnston et al., 2007; Figure 6.27). Johnston et al. (2007) modeled the availability of humpback whale wintering habitat within the Monument based on bathymetric and sea surface temperature data. This modeling indicates potential available humpback whale habitat at all islands and atolls in the NWHI (and at Maro Reef and Ladd Seamount) south of the 21.1°C sea surface temperature cline. These areas in 2007 totaled 14,700 km², compared to 7,200 km² of humpback wintering habitat available in the MHI (Johnston et al., 2007). Surveys (aerial and ship-based) of the NWHI conducted in 1976-1977 (November-April) returned no sightings of hump-

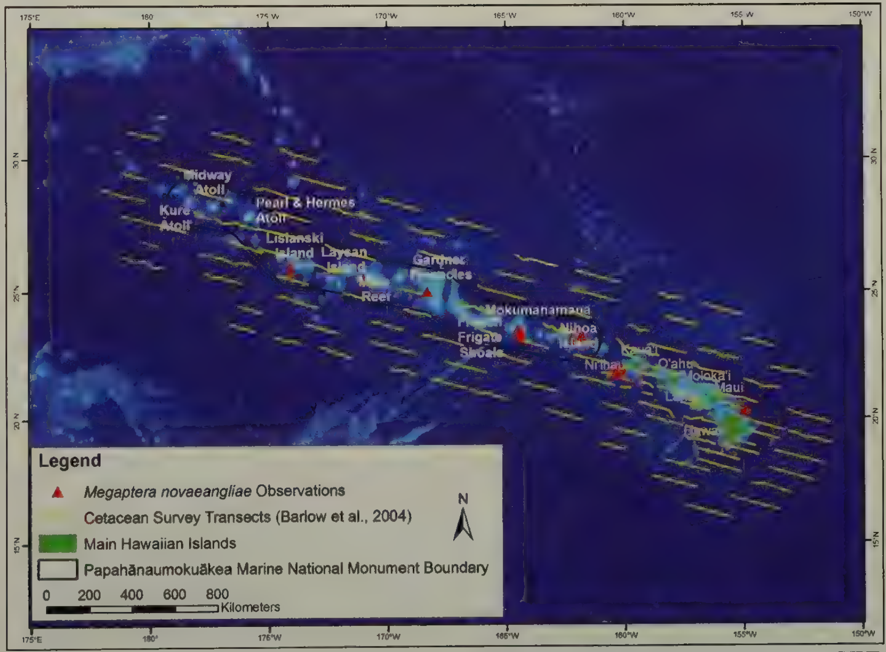


Figure 6.27. Humpback whale observations in the Hawaiian Island EEZ. Sources: Barlow et al., 2004; Johnston et al., 2007; NMFS, unpublished; map: K. Keller.

back whales (Herman et al., 1980). However, since the mid-1990s, regular sightings of humpback whales each year from January through March have been made by U.S. Fish and Wildlife Service staff stationed at French Frigate Shoals (A. Anders, pers. comm.). One reported opportunistic sighting of a mother and calf at French Frigate Shoals in February 1977 was dismissed as a "straggler" (Herman et al., 1980). This may suggest that the NWHI provide winter habitat for an expanding humpback whale population (Johnston et al., 2007).

Additional Cetacean Species

In addition to the 23 species described above, two other cetacean species have been detected within the Hawaiian Islands EEZ, including the North Pacific right whale (*Eubalaena japonica*) and blue whale (*Balaenoptera musculus*; Barlow, 2006). North Pacific Right whales have been observed in the waters surrounding the MHI on two confirmed occasions (Rountree et al.,1980; Tomich, 1986). The first record comes from a whaling ship's logbook from 1851 in which a single "straggler" was observed 250 nm west of Maui (Rountree et al., 1980). Tomich (1986) noted a sighting of an individual right whale swimming among a group of humpback whales between Maui and Lanai in March 1979. Blue whales have been detected, based on vocalizations, off of the coast of Oahu and it was suggested that they migrate past the Hawaiian Islands twice a year (Thompson and Friedl, 1982). Twenty hertz signals, similar to those recorded by Thompson and Friedl (1982), have also been reported near Midway Atoll (Tomich, 1986).

Cetacean Abundance Estimates

The 2002 cetacean survey conducted by Barlow et al. (2004) in the Hawaiian Islands EEZ allowed for the calculation of abundance and density estimates for 19 of the 23 species observed (see Barlow 2006 for description of analytical methods).

PINNIPEDS

The Hawaiian monk seal (*Monachus schauinslandi;* Figure 6.28) was listed as Depleted under the MMPA and Endangered under the ESA in 1976. The current population estimates are around 1,100-1,200 individual seals, the majority of which live in the NWHI.

The genus *Monachus* is a wide ranging species and is found in several different geographic areas around the world (Figure 6.29). The genus includes the Mediterranean monk seal (*Monachus monachus*), the Caribbean monk seal (*Monachus tropicalis*) and the Hawaiian monk seal. The Mediterranean monk seal is critically endangered and the Caribbean monk seal is assumed to have gone extinct in the last 50 years (Kenyan, 1977; see Boyd and Stanfield). The Hawaiian monk seal populations are estimated to have declined by 60% since the 1950s (Antonelis et al., 2006).

Range

Based on anatomical features and DNA analysis researchers estimate that Hawaiian monk seals arrived in Hawaii 14-15 million years ago (Repenning et al., 1979) and split from the *Monachus* ancestors around 11.8 to 13.8 million years ago (Flyer et al., 2005). Hawaiian monk seals occur within the Hawaiian EEZ and the main subpopulations occur in the NWHI. A smaller but potentially increasing population of seals inhabit the MHI and there have been occurrences including a documented pupping and relocations of aggressive males to Johnston Atoll. The monk seal metapopulation can be divided into six major and two smaller subpopulations in the NWHI and one in the MHI (Figure 6.30). These subpopulations are further grouped into management units.

Figure 6.28. There are an estimated 1,200 Hawaiian monk seals, the majority of which live in the NWHI. In 1976 the species was listed as Endangered under the ESA. Photo: J. Watt.

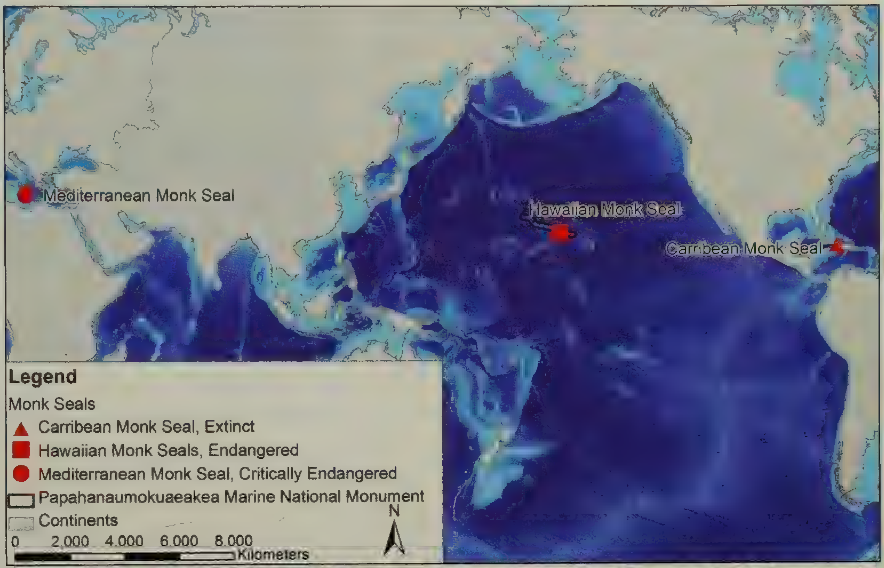

Mediterranean Monk Seal
Hawaiian Monk Seal
Carribean Monk Seal
Legend
Monk Seals
▲ Carribean Monk Seal, Extinct
■ Hawaiian Monk Seals, Endangered
● Mediterranean Monk Seal, Critically Endangered
Papahanaumokuaeakea Marine National Monument
Continents
N
0 2,000 4,000 6,000 8,000
Kilometers

Figure 6.29. Worldwide distribution of monk seals. Source: ESRI; map: K. Keller.

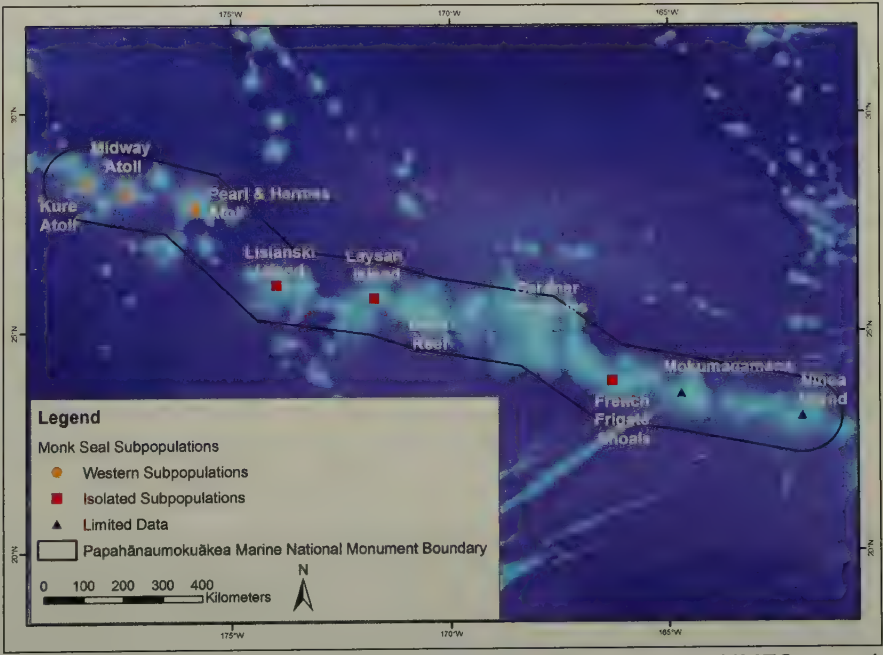


Figure 6.30. Hawaiian monk seal subpopulations. Source: NMFS, unpub data; map: K. Keller.

Available Data

The U.S. Fish and Wildlife Service conducted periodic monitoring of Hawaiian monk seals from the late 1950s until the late 1970s when the National Marine Fisheries Service (NMFS) assumed responsibility for recovery of the species and commenced monitoring activities. NMFS began an annual monitoring of Hawaiian monk seals at most major sites in the early 1980s. There is no historic data for estimating population size prior to the surveys of the 1950s or to estimate carrying capacity. It is likely that upon arriving in the MHI, Polynesian settlers extirpated the local population of seals. The surveys of the NWHI in the 1950s were too soon after World War II for the population to have plausibly recovered from the impact of the military disturbance, and some military presence was still having a negative effect on the monk seals at that time.

The first range-wide surveys of Hawaiian monk seals were conducted in the late 1950s (Kenyon and Rice, 1959; Rice, 1960). Additional counts were conducted at Midway Atoll in 1956-1958 (Rice, 1960) and at Kure Atoll in 1963-1965 (Wirtz, 1968). Surveys were repeated throughout the 1960s and 1970s, and while the methods were not standardized, complete beach counts are roughly comparable between the two survey periods.

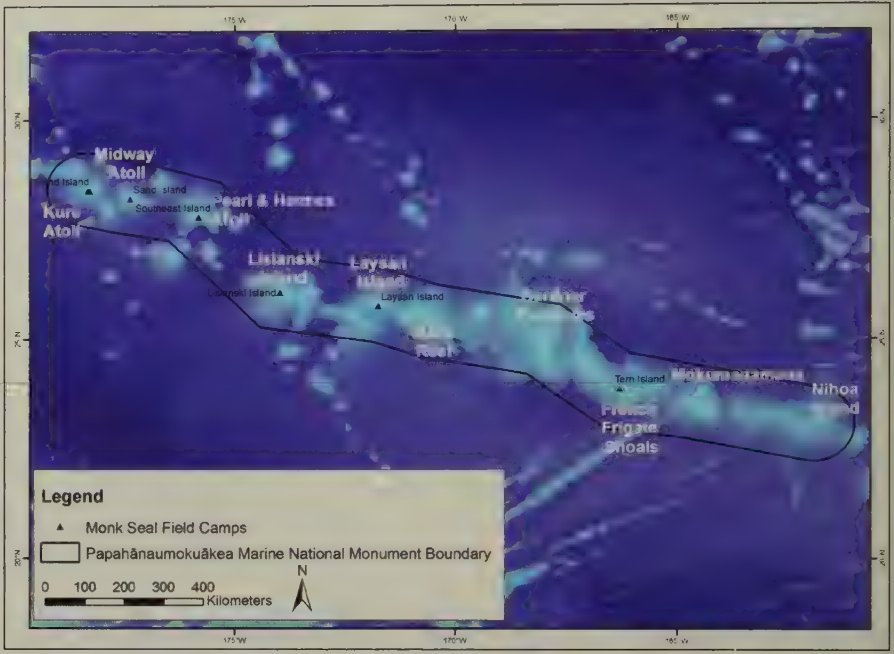


Figure 6.31. Hawaiian monk seal field camps. Map: K. Keller.

Since the early 1980s NMFS has been conducting annual surveys using standardized methods to estimate the population of Hawaiian monk seals. The work is conducted at field camps that are active from approximately April through August (Figure 6.31). All of the field camps collect information on the numbers of seals in the subpopulations based on counts of uniquely-identified seals. In addition any births, deaths, serious injuries and entanglements are documented. Necropsies are conducted on dead seals and seal feces are collected to evaluate dietary information.

Habitat Use and Foraging Behavior

Between 1996 and 2002, the movements and diving patterns of 147 Hawaiian monk seals have been monitored with satellite-linked radio transmitters at the six breeding colonies in the NWHI (42 adult males, 35 adult females, 29 juvenile males, 14 juvenile females, 12 weaned male pups, 15 weaned female pups; Abernathy and Siniff,1998; Stewart, 2004a, b; Stewart and Yochem, 2004a, b, c).

Parrish et al. (2000) attached animal borne imaging systems (Crittercams) to 24 adult and subadult male monk seals at French Frigate Shoals. The Crittercams recorded the habitat depth and bottom type at locations where monk seals were seen capturing prey items. Recent studies have focused on characterizing juvenile monk seal habitat use and foraging behavior at French Frigate Shoals using Crittercams and time-depth recorders (TDRs).

Abundance

NMFS field camps were initiated in the early 1980s using systematic surveys for estimating abundance of the Hawaiian monk seal populations. The abundance of monk seals at the six main reproductive sites in the NWHI is estimated by direct enumeration. At those locations the majority of individual seals can be identified by flipper-tags that have routinely been applied to weaned pups since the early 1980s, bleach marks placed annually, and by natural features such as scars and distinctive pelage patterns (Harting et al., 2007). The methods are different at Mokumanamana and Nihoa Islands because they are difficult to reach and there are no regular field camps at those sites.

The methods used to derive estimates of monk seal abundance, and the abundance at locations within the Monument and in the MHI are as follows:

- Main reproductive sub-populations in the NWHI of French Frigate Shoals, Laysan, Lisianski, Pearl and Hermes Atoll, Midway Islands and Kure Atoll: total enumeration of individuals when possible, otherwise capture-recapture estimates or minimum abundance (Baker, 2004; Baker et al., 2006).
- Mokumanamana and Nihoa Islands: corrected mean beach counts made during most recent five years at Mokumanamana and Nihoa Islands. A correction factor (2.89 ± 0.06; NMFS, unpubl. data) derived from observations at the main reproductive sites is applied.
- MHI: Minimum abundance consisting of the total number of uniquely identifiable seals observed alive during a calendar year. Sightings are non-systematic and collected by NMFS, and reported by volunteers, partner agencies and the general public.

Beach Counts

Methods

Beach counts are conducted at least eight times annually per site to calculate a mean value that serves as a trend index for long-term comparisons. The beach counts include a count of all the seals found on the island or group of islands within an atoll during a single mid-day survey.

Uses

Direct enumeration data cannot be used for comparing historical counts; however, a measure of long-term trend is derived from the mean of all of the beach counts that have been conducted with varying frequency since the late 1950s. These beach counts provide a useful index because the general methodologies of counts during these 45 years are roughly comparable.

Limitations

A consideration when interpreting the mean beach counts is that the relationship between the mean beach counts and the actual population size is uncertain. That is, all of the factors that might cause beach counts to deviate from the true abundance (for example, changes in haul out patterns over time) are not known, and hence appropriate correction factors have not been determined. Eberhardt et al. (1999) concluded that, "beach counts may be very poor guides to year-to-year trends. However, beach counts are valuable indicators of long-term trends." NMFS is currently investigating other approaches for estimating total abundance to better characterize long- and short-term trends.

Habitat Use

Terrestrial Habitat Use

Monk seals use terrestrial habitat for haul-out areas to rest and pupping. Haul-out areas for resting generally consist of sandy beaches, but virtually all substrates, including emergent reef and shipwrecks, are used at various islands. Monk seals also use the vegetation behind the beaches, when available, as a shelter from wind and rain. Pups are born on various substrates; however, sandy beaches with shallow protected water near shore seem to be preferred habitat for pupping and nursing (Westlake and Gilmartin, 1990).

Marine Habitat Use

Monk seals spend approximately two-thirds of their time in the marine habitat (MMRP, unpublished data). They are primarily benthic foragers (Goodman-Lowe et al., 1998), and will search for food in coral reef habitat and on substrate composed of talus and sand on marine terraces of atolls and banks to depths exceeding 500 m (Parrish et al., 2000, 2002: Parrish and Abernathy, 2006). Parrish et al. (2002) also described monk seals foraging in corals below 300 m in subphotic zones (Parrish et al., 2002).

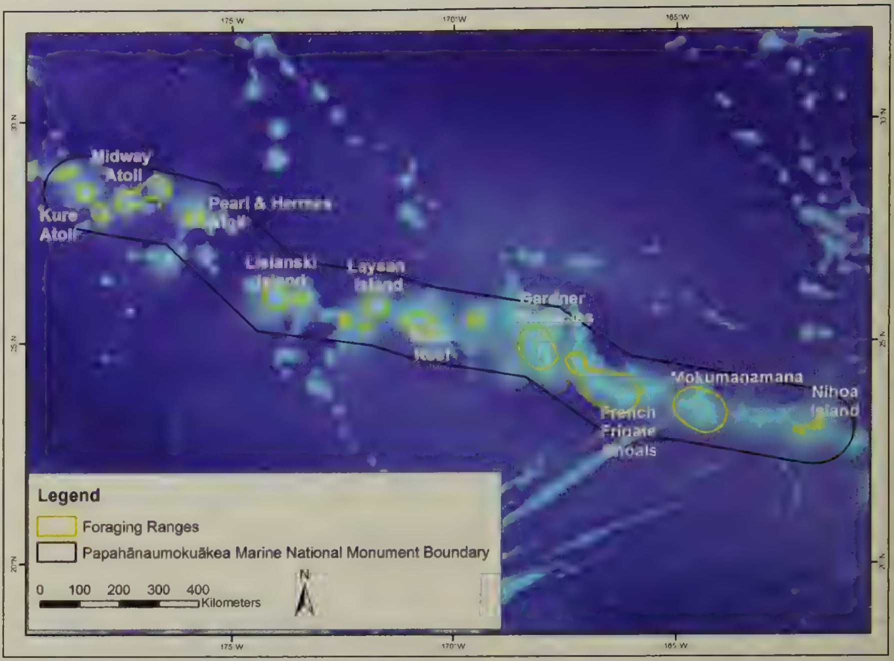


Figure 6.32. Hawaiian monk seal foraging ranges. Source: Stewart et al., 2006; map: K. Keller.

The largest study of monk seal foraging ranges and diving behavior was conducted using tagging information from 1996 to 2002 (Abernathy and Siniff, 1998; Stewart 2004a, b; Stewart and Yochem, 2004a, b, c). During this time the movements and diving patterns of 147 Hawaiian monk seals were monitored with satellite-linked radio transmitters at the six breeding colonies in the NWHI. Spatial dispersal of foraging seals indicates that they forage extensively within the lagoons at French Frigate Shoals, Pearl and Hermes Atoll, Midway Atoll and Kure Atoll, and on the outer slopes of those atolls and seaward of Laysan and Lisianski Island. Seals also foraged along the submarine ridges between these atolls and islands and at virtually all nearby seamounts. A fixed kernel density estimate method was used to determine the extent of foraging areas (Stewart et al., 2006; Figure 6.32). Primary foraging occurred in areas with high bathymetric relief or focused within the lagoon areas. At the majority of the islands and atolls 95% of the foraging occurred within 38 km and 75% occurred within 20 km of center of the island or atoll (Stewart et al., 2006). French Frigate Shoals did not follow this same pattern, however, with 95% of the foraging occurring within 50-58 km of the center of the atoll (Stewart et al., 2006). Seals at all of the colonies foraged outside of the colonies but there was no distinct pattern (Stewart et al., 2006; Table 6.2). Distances traveled to forage from haul out sites also varied with a seal's age and sex and with the seal's colony of seal origin. Foraging distances ranged overall from less than 1 km up to 217 km (Abernathy, 1999; Stewart, 2004a, b; Stewart and Yochem, 2004a, b, c; Stewart et al., 2006)

In addition to looking at the distances seals foraged from their colonies, the diving behavior was also monitored (Stewart et al., 2006; Table 6.2). Most frequently, seals dove to depths less than 150 m, though there were secondary diving modes at various depths up to 500 m. There was some variation in seals foraging depth between the island and atolls. At Pearl and Hermes Atoll 90 % of dives and at French Frigate Shoals 60 – 80% of dives were to depths of less than 40 m. The remaining 10 – 20% of dives occurred in depths greater than 40 m with some occurring as deep at 500 m. At Kure Atoll, Midway Atoll, Lisianski Island and Laysan Island seals regularly dived to depths greater than 40 m (Stewart et al., 2006).

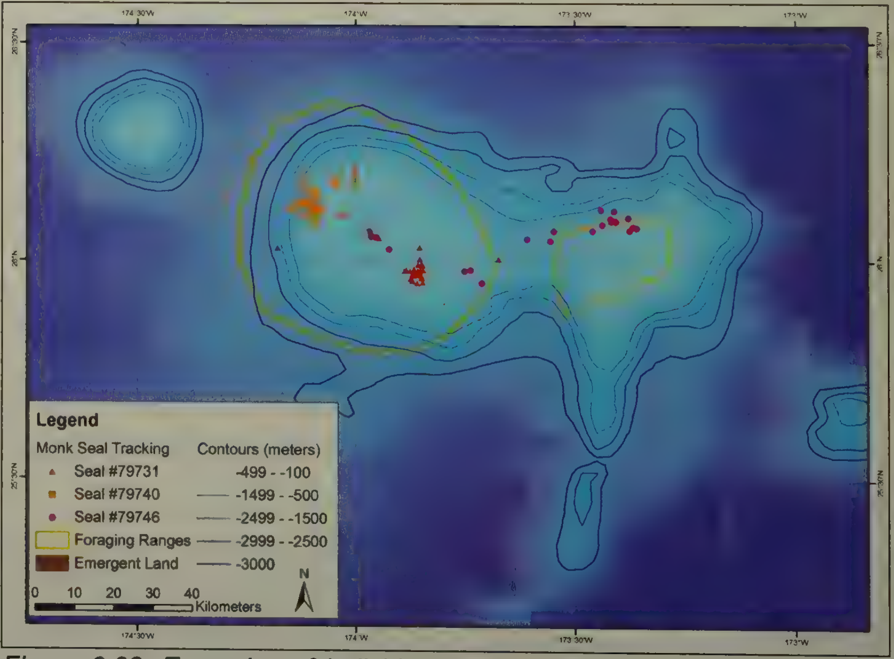


Figure 6.33. Examples of individual seal movements at Lisianski Island. Source: NMFS, unpub data; Stewart et al., 2006; map: K. Keller.

Foraging areas seem to vary between age groups, islands and individuals (Figure 6.33). Weaned pups at Kure Atoll and Midway Atoll did not range as far as adults whereas at Lisianski Island and Laysan Islands, adults and weaned pups exhibited similar foraging distances (Stewart et al., 2006). Further analy-

Table 6.2. Percentages of monitored Hawaiian monk seals at each colony that foraged at various sites in the NWHI. Source: Stewart et al., 2006.

FEATURE NAME	KURE ATOLL				MIDWAY ATOLL				PEARL AND HERMES ATOLL			LISIANSKI ISLAND				LAYSAN ISLAND				FRENCH FRIGATE SHOALS	
	WP (5)	J (11)	AM (4)	AF (4)	WP (4)	J (8)	AM (2)	AF (3)	J (6)	AM (9)	AF (9)	WP (8)	J (9)	AM (4)	AF (5)	WP (10)	J (10)	AM (5)	AF (5)	AM (17)	AF (17)
Un-named Kure Seamount 1			50																		
Un-named Kure Seamount 2			50																		
Un-named Kure Seamount 3			50																		
Kure Atoll	100	100	100	100		13	50	33													
Nero Seamount			25	25		13	50	33													
Midway Atoll				25	100	100	100	66													
Ladd Seamount				25				33	100	100	100										
Pearl and-Hermes Atoll								33													
Un-named PHR																					
Lisianski/ Neva Shoals												100	100	100	100						
Pioneer Bank												38	22		20						
Northampton W													11			30	30	20	40		
Northampton E													11					40	40		
Laysan													22		20	100	90	100	100		
Un-named Laysan 1													11								
Maro Reef													22			70	60	60	80		
Raita Bank																30	30	40	40		
Gardner Pinnacles																				6	30
St. Rogatien Banks																				12	10
Brooks Bank																				59	30
French Frigate Shoals																				100	80
Mokumanamana																					10

sis was conducted to examine the relationship between habitat use and diet composition. In the early 1990s 24 seals were tracked with satellite receivers and depth recorders at French Frigate Shoals (Parrish et al., 2000). In this study habitat use and diet of the monk seals were compared at different ecological zones. The analysis indicates that the seals foraging was focused more on the transitional slope areas. Generally the seals used all of the ecological zones proportionally to available habitat. The study also looked at the seals' diet and the availability of prey species in each zone. The diet derived from scat analysis did not correlate with the prey species composition in any of the individual zones which was expected as seals generally used multiple habitats over the course of foraging trips. An analysis of the dissimilarity index of prey biomass density found that the prey guilds documented in the bank and slope areas had the least deviation (Parrish and Abernathy, 2006).

Satellite tagging data provide basic information on where the seals travel but do not provide specific information about seal behavior during their dives so seal mounted video cameras were utilized to examine habitat use, prey selection, and foraging behavior. Parrish et al. (2000) found that the diurnal pattern of foraging by male adults occurred mainly at the 60 m isobath using data collected from Crittercams. A few seals foraged at depths of more than 300 m.

Crittercams also showed that even though much of the seals' time was spent in the shallow areas (<10 m) near colonies, the majority of the time searching occurred at greater depths (50 – 60 m). In addition, there was evidence of seals consuming prey at deeper depths. Seals targeted habitats that were low-relief and areas composed of loose talus fragments provided the best foraging habitat. In this habitat seals are able to dislodge the talus fragments and easily locate the prey species. The second most searched habitat type was sand-dominated areas where prey was easily accessible. These two habitats were more frequently searched and potentially provide higher return of prey for search effort than more complex coral habitats that offer more hiding locations for prey species (Parrish et al., 2000).

Recent studies have focused on characterizing juvenile monk seal habitat use and foraging behavior at French Frigate Shoals using Crittercams and TDRs. Juvenile seals forage in the same habitats commonly used by adults, but may lack the size and strength to forage as successfully as their adult counterparts (Parrish et al., 2005). Dive records have indicated that most dives occurred at depths less than 200 m, but occasionally some exceeded 200 m. Substantial variability among the pups in depth, duration and temporal patterns of dives was noted (NMFS, unpublished data).

Population Status and Trends

Current Abundance and Distribution of Populations

Hawaiian monk seals occur as a single meta-population, with subpopulations distributed among eight NWHI locations from Nihoa Island to Kure Atoll, as well as a small and likely growing subpopulation in the MHI. There has been variation in the population dynamics between the subpopulations, with differences in environmental conditions and levels of human disturbance contributing to this variation (NMFS, 2007; Figure 6.34).

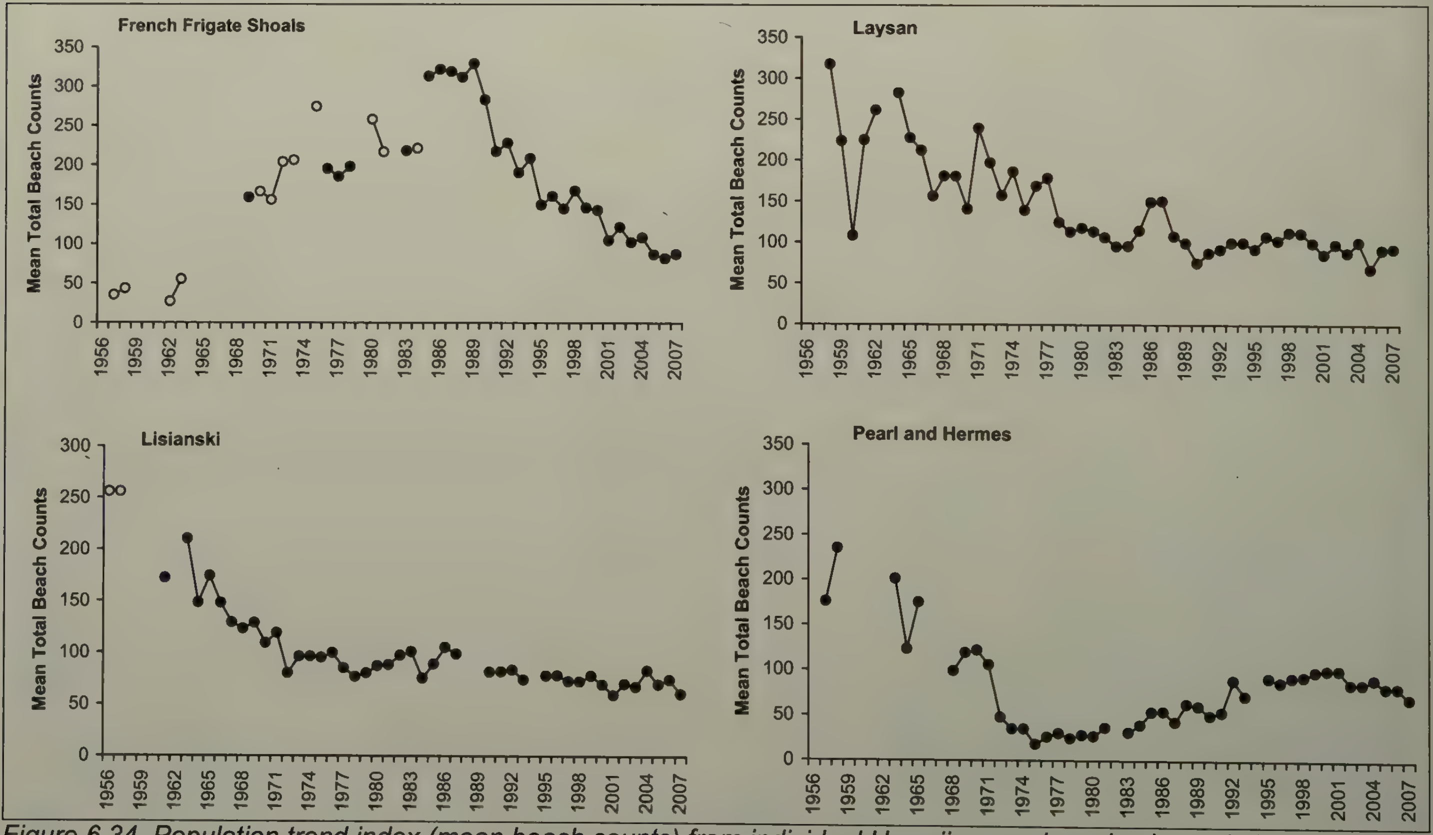


Figure 6.34. Population trend index (mean beach counts) from individual Hawaiian monk seal subpopulations (--o-- indicates less reliable historical counts). Source: NOAA PIFSC, unpublished data.

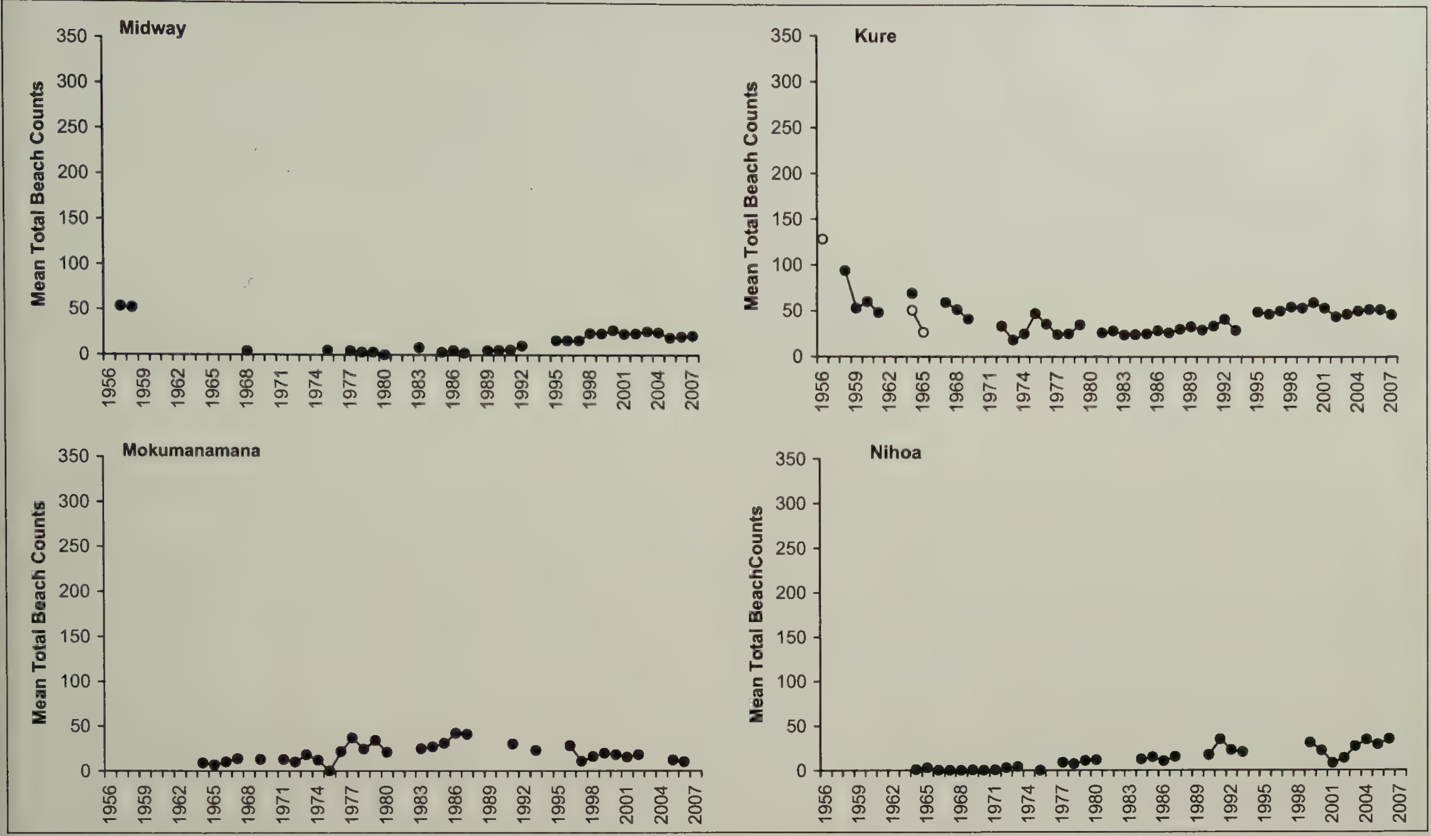


Figure 6.34 (continued). Population trend index (mean beach counts) from individual Hawaiian monk seal subpopulations (--o-- indicates less reliable historical counts). Source: NOAA PIFSC, unpublished data.

Population Trends Across the Northwestern Hawaiian Islands

The six major subpopulations in the NWHI can be divided into the three western subpopulations at Kure Atoll, Midway Atoll and Pearl and Hermes Atoll; and the more geographically isolated populations found at Laysan and Lisianski Islands, as well as French Frigate Shoals. The higher exchange of individuals between the western subpopulations may contribute to observed similarities in population dynamics among these sites, and these islands may, in certain circumstances, be considered a single management unit. Table 6.3 illustrates the variation in abundance estimates between the different islands and atolls in 2007.

Table 6.3. Estimated 2007 monk seal abundance for each population segment. Nmin calculated at Mokumanamana and Nihoa Islands according to the methods of Wade and Angliss (1997). Source: NMFS, unpublished data.

SITE	ESTIMATION METHOD	Nmin	Nbest
French Frigate Shoals	Minimum	228	228
Laysan Island	Minimum	209	209
Lisianski Island	Total enumeration	174	174
Pearl and Hermes Atoll	Minimum	154	154
Midway Island	Minimum	65	65
Kure Atoll	Minimum	105	105
Mokumanamana	Corrected beach counts	31.4	42
Nihoa Island	Corrected beach counts	72.2	78.7
Main Hawaiian Islands	Minimum	88	88
Total		**1,126.60**	**1,143.70**

The estimated probabilities of sighting an animal is 90% for all years of data at French Frigate Shoals, Laysan Island, Midway Atoll and Kure Atoll, approximately 85% at Lisianski Island, and approximately 80% at Pearl and Hermes Atoll (Harting, 2002). Therefore, the numbers may underestimate the size of those sub-populations by 10%-20%. The methods used for the other population components (Mokumanamana, Nihoa and the MHI), while somewhat less accurate, are the best possible under current budget and logistical constraints. Because the other population segments represent relatively small proportions of the total population, errors in their abundance estimates do not greatly distort the estimated total population size. For example the best estimate of the total population size in 2005 was 1,247 seals. To determine a minimum population estimate (Nmin) for the total population that accounts for the statistical uncertainty in the abundance estimates, as is done for stock assessment reports required by the MMPA (Wade and Angliss, 1997), a combination of enumeration and minimum estimates was used. The number of seals identified in 2005 at the main reproductive sites was 1,065 seals, including 163 pups. Minimum population sizes for Mokumanamana and Nihoa Islands (based on the formula provided by Wade and Angliss, 1997) were 34 and 39, respectively, and a total of 77 seals were identified in the MHI. Using that procedure, minimum population size estimate for the total population is the sum of these estimates, or 1,215 seals.

Long-term and Recent Population Trends

Beach counts are used as an index of the population size. Based on the beach counts from the 1950s to 2001 it appears that the species declined by approximately 50% between the late 1950s and the mid 1970s (Kenyon, 1973; Johnson et al., 1982). Beach counts of non-pups (juveniles, sub-adults and adults) declined by 68% between the years 1958 and 2005.

Based on the very limited window of data availability, the largest counts of monk seals observed at many islands were obtained around 1958. Three exceptions to this were French Frigate Shoals, where the maximum count was obtained in 1985, Mokumanamana where the maximum was obtained in 1977, and Nihoa where the maximum was obtained in 1991. The sum, across all sites in the NWHI, of the maximum counts, whenever obtained, totals 1,541, corresponding, after a very uncertain correction, to an estimated population size of around 3,000. There is evidence, at a minimum, that the available habitat was probably capable of supporting at least 3,000 monk seals in the NWHI plus an unknown number in the MHI.

More recent data indicate that non-pup beach counts declined rapidly from 1985 to 1993, became relatively stable for several years, then declined again beginning in 1998. Models estimate that the total counts declined 8.1% per year until 1993 (Carretta et al., 2005). The trend in total abundance of Hawaiian monk seals is shown in Figure 6.35. A log-linear regression of estimated abundance from 1998 (the first year for which a reliable total abundance estimate has been obtained) to 2006 estimates that abundance declined -3.9% yr $^{-1}$ (NMFS, unpublished data).

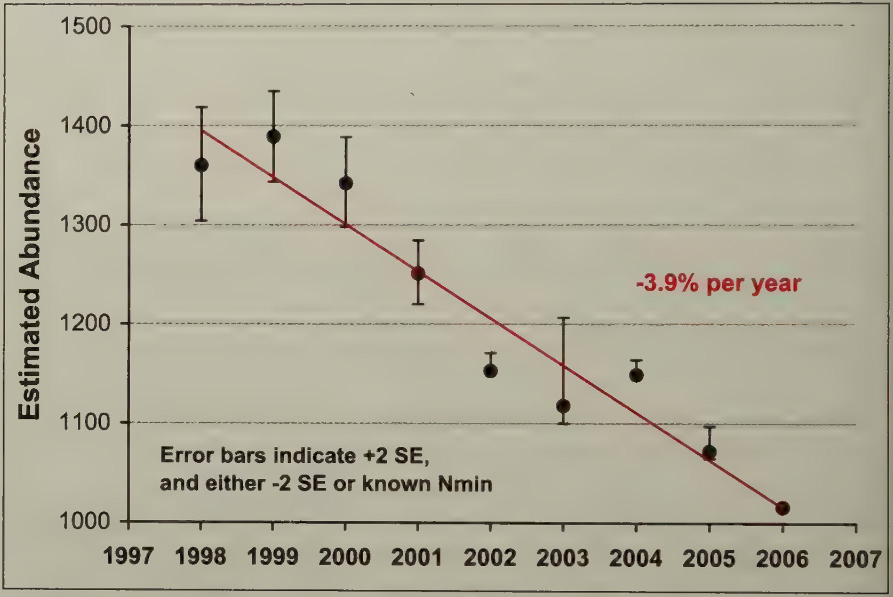


Figure 6.35. The long-term combined trend at the main NWHI sites masks a diversity of trends within the individual Hawaiian monk seal sub-populations. The population dynamics at the different atolls have varied considerably and current demographic variability among the island populations probably reflects a combination of human and environmental/natural influences. Source: Gerrodette and Gilmartin, 1990; Polovina et al., 1994; Craig and Ragen, 1999; Ragen, 1999.

The Population Trends by Island and Atoll

In addition to examining the overall trend in the Hawaiian monk seal population it is also important to examine each island and atoll. Each subpopulation exhibits different population dynamics that reflect their unique histories and environmental conditions (Figure 6.34).

Kure Atoll

The Hawaiian monk seal population at Kure Atoll has been impacted over the years by human disturbance. Beginning with sailors stranded after the ship wreck of the *Parker* who killed seals for food and continuing with disturbance caused by the U.S. Coast Guard (USCG) LORAN station. In the late 1970s NMFS began efforts with the USCG to reduce the level of disturbance to the Hawaiian monk seals. USCG decommissioned the LORAN station in 1992. Since 1992 state of Hawaii Department of Land and Natural Resources and the Marine Mammal Research Program (MMRP) field camps are the only human presence at Kure Atoll during the summer months.

The population dynamics of monk seals have varied with these changes in human disturbance at Kure Atoll (Figure 6.34). After the construction of the LORAN station in the late 1950s and early 1960s the seal population declined abruptly. As efforts were made in the 1980s to reduce disturbance to the seals there was a corresponding increase in pup survival (Gerrodette and Gilmartin, 1990; Gilmartin, pers. comm.). From 1983-2000 the beach count data shows a 5% increase per year. Since 2000 as seen at other islands and atolls there has been high juvenile mortality. The increase in the population until 2000 has been attributed to the reduction of human disturbance by USCG regulations and the closure of the LORAN station (Gilmartin et al., 1986). In addition 54 immature female seals were released at Kure and reached reproductive maturity by the early 1990s. (NMFS, 2007). Recent trends indicate a decline in the Kure population.

Midway Atoll

Midway Atoll has also had a history of human disturbance, starting in 1859, which has impacted the Hawaiian monk seal population (Figure 6.34). The monk seal population was depleted by the late 1800s and partially recovered in the early 1900s. Human activities in the early 1900s included attempts to blast a ship channel, installation of a cable station, construction of an airport and other World War II military activities. After World War II the human population peaked at 3,500 and was reduced to 250 by 1978 (NMFS, 2007). The 1957-1958 monk seal surveys recorded a mean of 57 seals but by 1968 only one seal was observed (Kenyon, 1972). There were occasional sightings in low numbers during the 1980s (NMFS, 2007). Midway's small monk seal population saw increases in the early 1990s as management efforts were increased to reduce disturbance. By 1988 the U.S. Fish and Wildlife Service (USFWS) was actively participating in the management of wildlife at Midway Atoll in conjunction with the U.S. Navy. Since 1988, the USFWS has restricted the numbers of staff and visitors to Midway Atoll. Hawaiian monk seal beach counts increased during the 1990s but this was primarily due to immigration of individuals from Pearl and Hermes Atoll and Kure Atoll. In addition to immigrants, there were increases in total births. In 1996 the Navy transferred Midway Atoll to the USFWS and further measures were put in place to reduce disturbance to monk seals. There was a short five year increase in beach counts from 1995 – 2000 followed by a decline since 2000.

Pearl and Hermes Atoll

Impacts on the seal population at Pearl and Hermes Atoll started in 1859 when a sealing expedition visited the atoll. In the late 1920s pearl oysters were harvested and construction occurred on the islands. The U.S. military occupied the atoll in 1961 during construction of an observation tower. The atoll is now unoccupied except for NMFS summer field camps.

The Pearl and Hermes Atoll seal population declined by an estimated 90% after the 1950s (Figure 6.34). From the mid-1970s to 2000 beach counts have increased. Specifically from 1983 to 2000 counts increased an average of 6%. As seen at Kure Atoll and Midway Atoll counts have declined since 2000.

Lisianski Island

Lisianski Island is the site of many 1900s ship wrecks and as seen with other wreck sites stranded sailors relied on monk seals as well as other species for food. Harvesting expeditions also occurred during this time. Today the island is unoccupied except for monk seal field camps.

Beach counts have declined since the late 1950s and have remained low since then (Figure 6.34). The island is estimated to be below the carrying capacity but the cause for low population size is unknown.

Laysan Island

The 1857 Hawaiian vessel *Manuokawai* reported Hawaiian monk seals at Laysan Island. By the 1900s seal expeditions and guano miners had nearly extirpated the seal population. For several years the Japanese collected eggs and feathers from the island but since this collection was halted in 1915, the island has been relatively undisturbed by human presence. The only activities since that time have been survey and scientific expeditions. Beginning in the early 1990s the USFWS has had a small year round field camp on Laysan, and NMFS has conducted seasonal field camps on the island.

As on other islands, Laysan's monk seal population declined in the late 1950s. The population has seen some increases but is still below the historic high. Ciguatera is suspected in a mass die off of 50 seals in 1978, but was not conclusively proven. In the early 1980s the sex ratio at Laysan was male biased resulting in 45 confirmed deaths due to male aggression from 1982 – 1994. From 1983 – 1994 an average of 4% of the Laysan adult females died from injuries related to male aggression (Johanos et al., 1999). Interventions to remove subordinate males and correct the sex ratio were successfully undertaken in the mid-90s and have resulted in substantially fewer occurrences of male aggression. Even though juvenile survival at Laysan is better than French Frigate Shoals there are still concerns about food limitations. There is still not a good understanding of the underlying causes or the lack of recovery of the monk seal population at Laysan Island.

French Frigate Shoals

French Frigate Shoals did not have the same guano resources that other islands in the NWHI did. As a result, the atoll was not mined; however, there is still documentation of harvesting occurring in 1882 of sharks, turtles, beche-de-mer and birds. The highest level of use occurred during World War II when a Naval airbase was built on Tern Island in 1942. A USCG LORAN station was established and maintained on East Island from 1943 - 1952. The Naval airbase on Tern Island was decommissioned in 1946 but the USCG maintained the island as a LORAN station from 1952-1979. Since the closure of the USCG LORAN station the USFWS has operated a field station on Tern Island.

French Frigate Shoals currently supports the largest monk seal colony in the NWHI (Figure 6.34). The monk seal population at East Island and Tern Island were impacted by disturbances caused by the military and USCG presence; however, after the closure of the LORAN station in East Island, numbers of monk seals using the island increased until the 1980s. After the USCG left Tern Island the presence of seals at the island increased until 1989. Since 1989 the French Frigate Shoals population has declined by as much as 75%. Juvenile survival rates have declined during this time. Survival in the mid-1980s for weaning to age two was as high as 90% but dropped to a low of 8% in 1997. One result of the low survival rates is an imbalance in the age structure of the population. The overall population is expected to decline in coming years as fewer females reach reproductive age and older females die.

Mokumanamana and Nihoa Island

Population monitoring visits to Mokumanamana and Nihoa Islands are infrequent and brief, so enumeration is not possible at these sites. Counts of seals at those islands tended to increase from approximately 1970 to 1990 (Figure 6.34). The increase in counts may have been due to an influx of seals from French Frigate Shoals, which was growing at that time. During a seven-day period at Mokumanamana in 1993, 14 tagged seals were sighted, all of which had been marked as pups at French Frigate Shoals (Finn and Rice, 1994). During the same period, 12 tagged seals were sighted at Nihoa Island, 10 of which were from French Frigate Shoals (Ragen and Finn, 1996).

The Main Hawaiian Islands

The number of documented monk seal sightings in the MHI increased during the 1990s. Historical abundance data for the MHI are limited, as there were no systematic surveys of monk seals conducted prior to 2000. Births in the MHI have become more frequent. The known number of annual births in the MHI before and during the 1990s was usually zero and never exceeded four, but seven births were recorded in 2000 and 12 in 2001 (Baker and Johanos, 2004). More recently, a minimum of 88 individual seals have been identified in the MHI (NMFS, unpublished data).

MARINE TURTLES

Covering more than 360,000 km² of subtropical waters in the North Pacific, the Monument provides critical breeding and nesting habitat for the green turtle (Figure 6.36), and foraging habitat and migration pathways for green loggerhead, hawksbill and leatherback (Figure 6.36) turtles. Although olive ridley turtles have not been sighted within the Monument, their known distribution in the tropical Pacific indicates that they likely also use waters of the NWHI (Papahanaumokuakea Marine National Monument, 2008). These five marine turtle species are all protected under the ESA due to threats to beach nesting habitat and from incidental bycatch, marine debris entanglement, and vessel strikes (http://www.nmfs.noaa.gov/pr/species/turtles/).

Although four marine turtle species have been documented in Monument waters, the extensive nesting of green turtles in the NWHI has allowed for multi-island surveys, capture-mark-recapture work and long-term population studies of this species (Figure 6.37). Based on green turtle basking and nesting surveys across islands/atolls and over time, the species basks throughout the NWHI (Figure 6.38), but nests at only a subset of the islands (Figure 6.39).

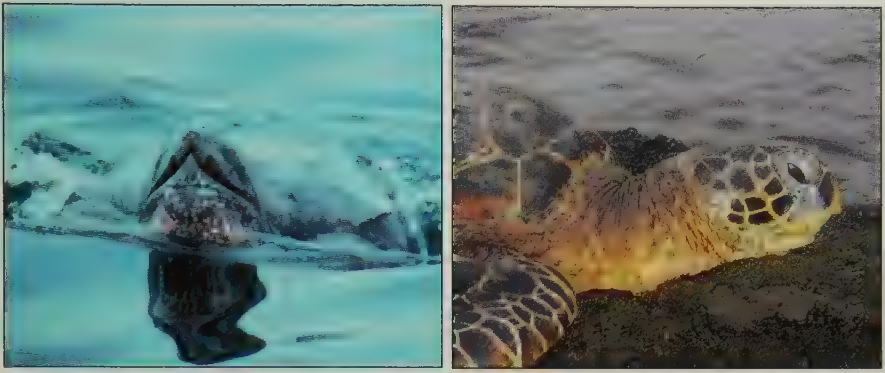


Figure 6.36. Leatherback turtles (left) and the Hawaiian green turtle (right) can be found in the Monument. Photos: NOAA National Marine Sanctuaries.

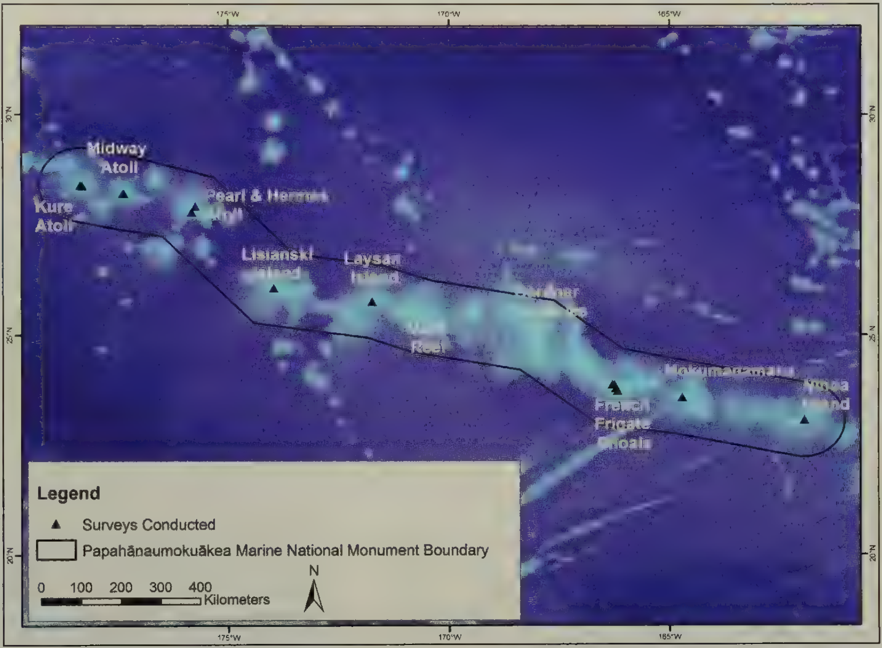


Figure 6.37. Locations of green turtle basking and nesting attempt surveys conducted within the NWHI. Map: K. Keller.

Monitoring Efforts by Island: Data and Methodology

French Frigate Shoals

More than 90% of Hawaiian green turtle nesting occurs at French Frigate Shoals, with over 50% of nesting occurring on East Island. In addition to intensive study of green turtles at this atoll, annually since 1973, early observations were made by military personnel, fishermen and scientists at French Frigate Shoals beginning in 1859. Amerson (1971) summarizes all known observations of basking green turtles and nest attempts from 1859 through 1969.

The largest data set on green turtles in the NWHI consists of 35 years of research, beginning in 1973, on the nesting population on East Island, French Frigate Shoals (Balazs and Chaloupka, 2006). Between 1973 and 1981, the work was a partnership between the Hawaii Institute of Marine Biology (University of Hawaii) and the USFWS, and since 1982 a collaboration between USFWS and the NOAA Pacific Islands Fisheries Science Center (PIFSC). From 1973 through the present time, annual surveys have been conducted on the number of individual female turtles going ashore each night during the nesting season (Balazs, 1976, 1980; Wetherall et al., 1998). Prior to 1996, unique individuals were identified based on double-tagging with external flipper tags; since that year, all individuals have been double-tagged with passive integrated transponders. Tagging studies have shown that nesting-island site fidelity is very high within the Hawaiian rookery, such that annual nesting abundance and trend estimates are not confounded by substantial immigration or emigration (Dizon and Balazs, 1982; Niethammer et al., 1997).

Annual nesting abundance at East Island, French Frigate Shoals, has been estimated by the PIFSC using a Horvitz-Thompson type estimator: $N_i = n_i/p_i$, where N_i = number female nesters in year i, n_i = number of uniquely-identified female nesters in year i, and p_i = probability of sighting a unique female that nests in year i. The value p_i was estimated based upon census data from >1,100 nesters during a five-year season-long saturation tagging and re-sighting program at the atoll from 1988-1992. Trends in nester abundance from 1973-2004 were estimated by Balazs and Chaloupka (2004, 2006) using a Bayesian smoothing spline regression that was fitted to the Horvitz-Thompson nest abundance series (Balazs and Chaloupka, 2004, 2006).

Other Islands and Atolls

Data on the number of green turtle pits and number of basking turtles at other islands and atolls in the northwestern chain have been collected in some years from 1982 through 2008. Number of pits does not indicate a specific number of nesting attempts by turtles, as each nesting attempt may consist of one too many pits; however, pits are likely indicative of some level of attempted nesting on the islands on which they have been observed (S. Kubis Hargrove, pers. comm.). On Laysan Island, NMFS personnel counted the number of turtle pits and basking turtles from March through June 1982 (Kam, 1986). In 2007, USFWS personnel surveyed the perimeter of Laysan Island regularly throughout the green turtle nesting season and monitored active nests for hatching (Payne et al., 2007). On Lisianski Island, NMFS personnel counted the number of pits dug and number of basking turtles through various portions of the nesting season each year from 1982 to 1987, and 2006 and 2007 (Kam, 1985; Kam, 1986; Alcorn et al., 1988; Johanos and Withrow, 1988; Westlake and Siepmann, 1988; Kubis, 2008; M. Snover, pers. comm.). Similar counts were done at Pearl and Hermes Atoll in 1982, 1990, 1991, 2006, and 2007 (Kam, 1986; Finn et al., 1993; Kubis, 2008; M. Snover, pers. comm.). At Midway Atoll, the first observation of nesting occurred in 2006, and nests were also documented in 2007 and 2008 (John Klavitter, pers. comm.). In addition to pit counts at these islands and atolls, in 2006 NMFS personnel quantified the mean numbers of basking turtles from May through August at all islands and atolls north of Mokumanamana (B. Becker, M. Snover, pers. comm.).

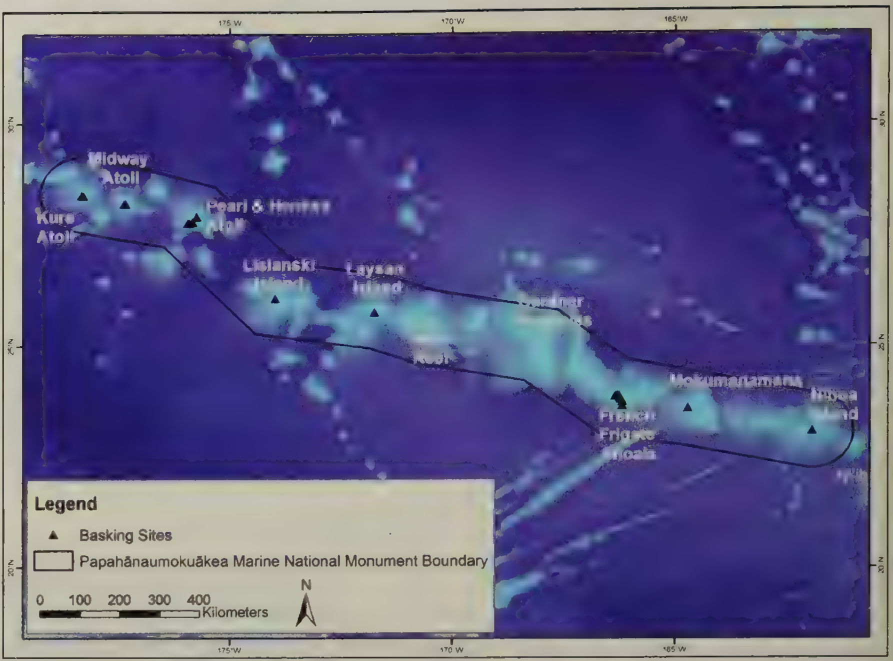


Figure 6.38. Islands and atolls at which green turtles have been observed to bask. Map: K. Keller.

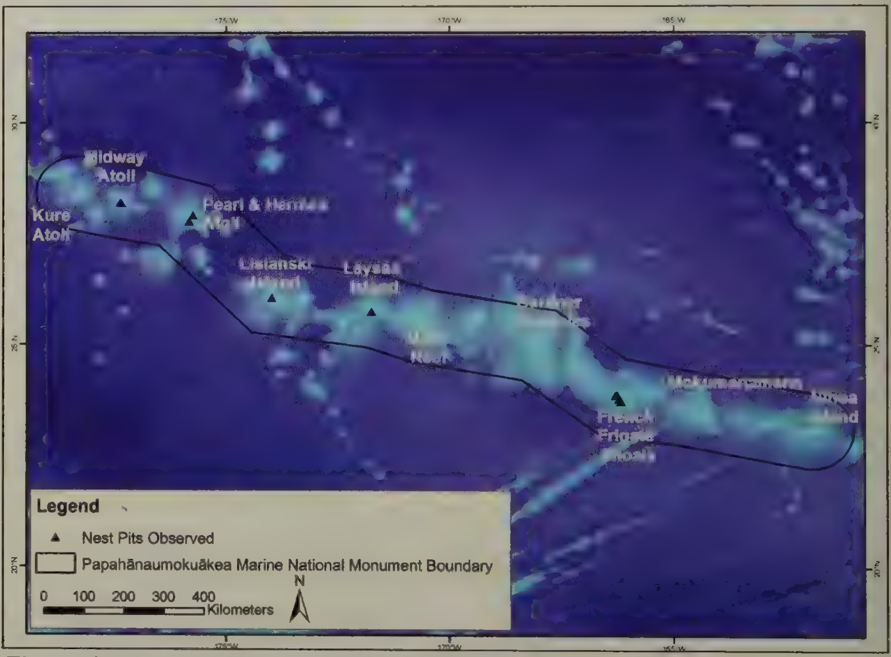


Figure 6.39. Islands and atolls at which green turtle nesting attempts (pits) have been observed. Map: K. Keller.

Results and Discussion

French Frigate Shoals

Amerson (1971) reports that green turtles were first recorded at French Frigate Shoals by personnel on the USS *Fenimore Cooper* in 1859. In 1882, the crew of the Japanese-owned schooner *Ada* reported collecting 1,543 pounds of turtle shell and 47 gallons of turtle oil from approximately 350 turtles. In 1914, green turtles were observed basking at French Frigate Shoals by the USS *Rainbow*'s hydrographic survey team, and in 1923, members of the *Tanager Expedition* also reported observing turtles and turtle eggs at the atoll. They also reported evidence of previous turtle slaughter (Amerson, 1971).

From the early 1920s through the late 1960s, U.S. Department of Interior, NOAA and the Smithsonian Institution personnel reported observing green turtles basking on most of the islands within French Frigate Shoals, including Tern, Trig, Whaleskate, Round, East, Gin, Little Gin and Disappearing Islands. The largest numbers of baskers during this time period were reported on East Island in the 1960s, with the highest number recorded (86 turtles) in September 1966. Turtle pits were also recorded through the late 1960s on Tern, Trig, Whaleskate, Round, East, Gin and Little Gin Islands (Amerson, 1971).

More recently, NOAA personnel have quantified the number of green turtles basking on all islands within French Frigate Shoals during the nesting season. In 2006, an average of 143 turtles was observed basking at any one time.

Results of Balazs and Chaloupka's research on green turtles nesting at East Island, French Frigate Shoals, indicate annually variable nesting population sizes, ranging from just under 100 to more than 500 female turtles each year from 1973 to 2004 (Figure 6.40). Estimation of nesting population trends indicates an increase in annual population size of approximately 5.7% per year (95% CI: 5.3 - 6.1%) over that 32-year time period (Figure 6.40; Balazs and Chaloupka, 2006).

The increase in green turtle nesting population size at French Frigate Shoals (Figure 6.41) may be attributed in part to increased protections under the ESA, as harvesting of turtles on land or in waters surrounding the Hawaiian Islands was prohibited beginning in the late-1970s. However, human impacts on beach nesting habitat at French Frigate Shoals also changed dramatically over the last half of the 20th century. From the late 1930s to early 1950s, the U.S. Navy and USCG operated Naval Air and Long Range Navigation stations on East Island; during that time, turtle nesting and basking reportedly greatly decreased (Amerson, 1971). After the decommissioning of the Naval Air Station and relocation of the USCG LORAN station from East Island to Tern Island in

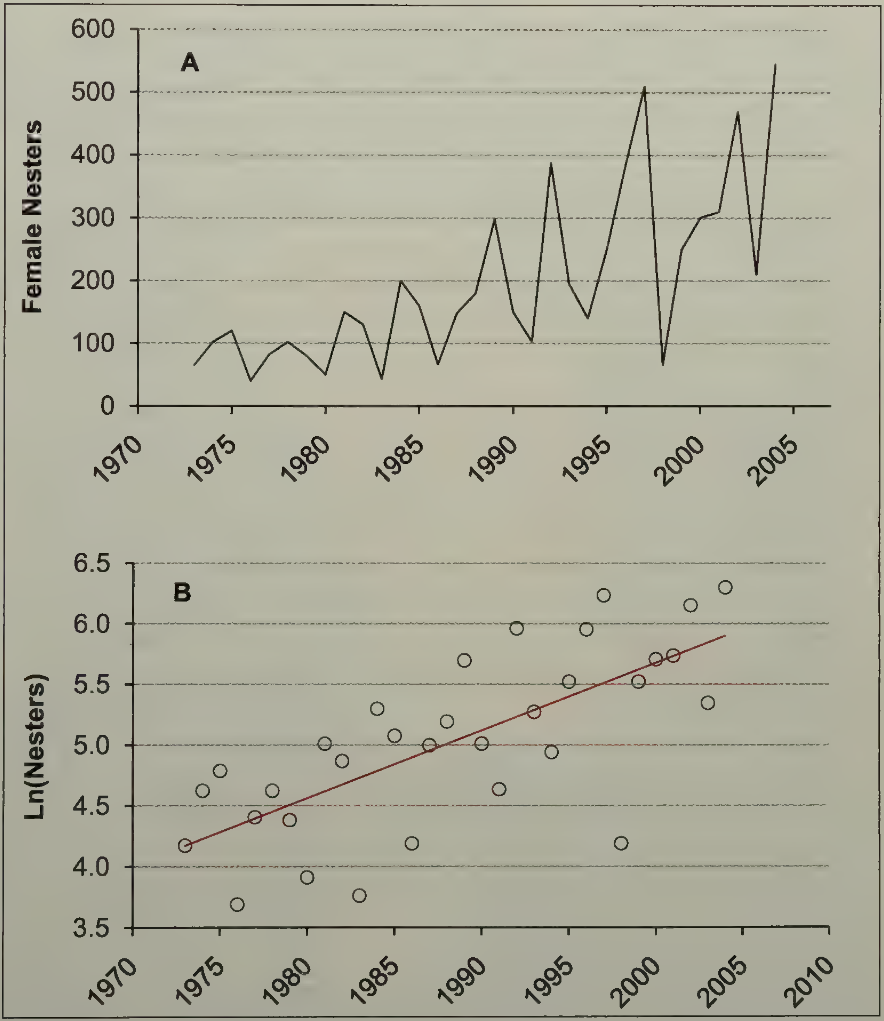


Figure 6.40. Trends in green turtle nester abundance at East Island, French Frigate Shoals, 1973-2004. Panel A shows time series plot of the Horvitz-Thompson estimate of number of female turtles nesting each year over the 32-year period. Panel B shows estimated long-term trend in nester abundance derived using Bayesian smoothing spline regression model, which was fitted to the Horvitz-Thompson nester series shown in panel A. Red curve is mean annual nester abundance. Source: Balazs and Chaloupka, 2006.

1954, numbers of nest attempts on East Island began to increase through the late 1960s (Amerson, 1971). The number of nest at French Frigate Shoals continued to increase through 2004 (Balazs and Chaloupka, 2006), and during the 2008 season, an estimated 589 females nested at East Island (G. Balazs, pers. comm.).

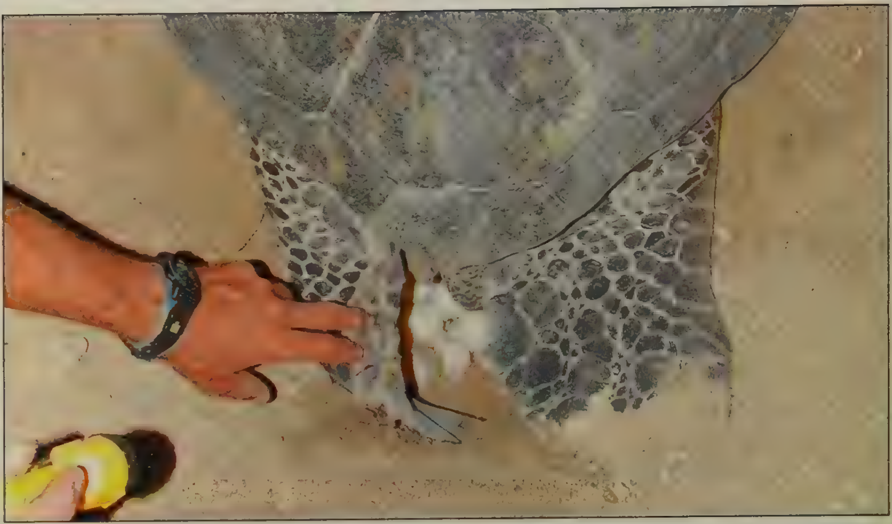


Figure 6.41. Green turtle laying eggs, French Frigate Shoals, June 2002. Photo: NOAA.

Other Islands and Atolls

Numbers of green turtle nesting and basking are much lower at the other islands and atolls in the northwestern chain, relative to French Frigate Shoals. The islands of Nihoa and Mokumanamana contain only small areas of basking habitat, while Laysan, Lisianski, and the islands of Pearl and Hermes Atoll have small numbers of nesting green turtles each year (fewer than 100 turtle pits per island or atoll). Midway and Kure Atolls have relatively extensive areas of beach habitat, but only one nest per year has been observed at Midway Atoll since 2006 (John Klavitter, USFWS, pers. comm.), and nesting has never been observed at Kure Atoll (Kubis, 2008). The following sections provide results of pit and basking turtle counts for Nihoa, Mokumanamana, Laysan, Lisianski, Pearl and Hermes Atoll, Midway Atoll and Kure Atoll for some years from 1982 through 2008.

Nihoa and Mokumanamana

The two high islands of the northwestern chain, Nihoa and Mokumanamana, each contain habitat for basking and/or nesting, although consisting of only several square meters. There is a small sand beach at Nihoa, but only rocky shoreline on Mokumanamana. Green turtles have not been observed nesting on either of these islands, but basking has been observed (Kubis, 2008). In 1983, NOAA personnel recorded a mean of 1.5 basking turtles per day on Mokumanamana from 24 July through 6 August (Morrow and Buelna, 1985).

Laysan Island

In 1982, NOAA personnel on Laysan Island observed 12 green turtle nest excavations, consisting of 45 pits, between 25 May and 30 June. In addition, a mean of 2.6 turtles were observed basking each day during the period 16 March through 30 June (Kam, 1986).

In 2005 and 2006, USFWS personnel noted a "few" green turtle pits on Laysan from April through October (C. Rehkemper, USFWS, pers. comm.), and in 2006 NMFS personnel recorded 0.2 turtles basking at any one time during the nesting season (M. Snover, NMFS, pers. comm.).

In 2007, USFWS located a total of 50 green turtle nests on Laysan (Figure 6.42). Of 24 nests that were monitored from May through early September, an estimated 1,403 eggs were laid, with clutch sizes ranging from 55 to 111 (mean = 87.8, n = 16 nests). Hatching success at the 24 monitored nests was 85.6%. Incubation periods ranged from 60-75 days (mean = 67.5), with incubation period shortening over the course of the season (Payne et al., 2007).

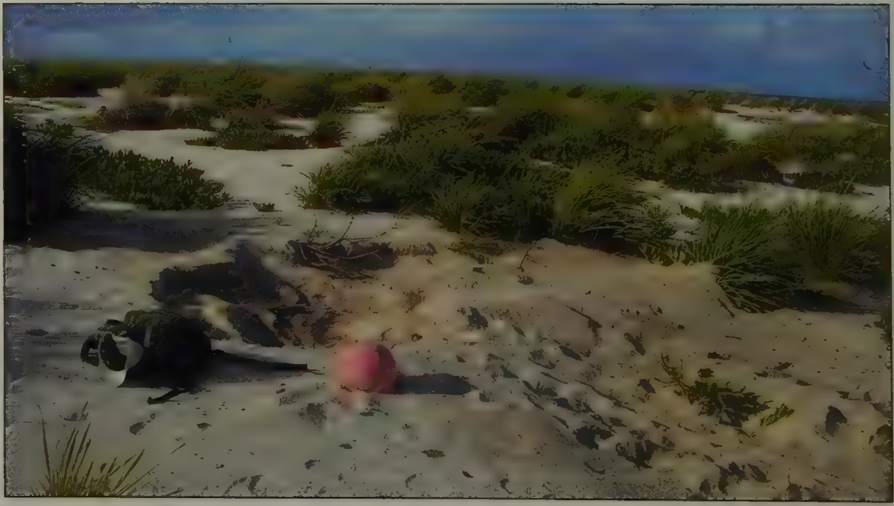


Figure 6.42. Green turtle nest on Laysan Island, 26 June 2007. Photo: USFWS.

Lisianski Island

NMFS personnel counted turtle pits and basking green turtles on Lisianski Island during parts of the nesting season in some years between 1982 and 2007. Results of these counts indicate a range of 15 to 47 pits observed per year, and a mean of 2.0 to 5.4 turtles basking on the island per day (Table 6.4). Figure 6.43 indicates the locations of pits observed on Lisianski Island in 1982 and 1983.

Table 6.4. Observations of pits and basking green turtles on Lisianski Island, 1982–2007.

YEAR	DATES	OBSERVATIONS	REFERENCE
1982	May – Aug	23 excavation sites consisting of 47 pits	Kam (1986)
1982	8 Jul – 13 Sep	Mean of 5.4 baskers/day	Kam (1986)
1983	31 May – 9 Aug	19 pits (Figure 6.43)	Kam (1985)
1984	2 Jul – 6 Aug	91 pits	Alcorn et al. (1988)
1985	17 Jun – 20 Jul	78 pits	Alcorn et al. (1988)
1986	5 – 26 Aug	15 pits	Westlake and Siepmann (1988)
1987	1 – 4 Jun; 5 – 29 Aug	34 pits	Johanos and Withrow (1988)
1987	7 – 27 Aug	Mean of 2.0 baskers/day	Johanos and Withrow (1988)
2006	May – Aug	Mean of 2.9 baskers/day	Melissa Snover, NMFS (pers. comm.)
2007	May – Jun	Nests observed but not counted	Kubis (2008)

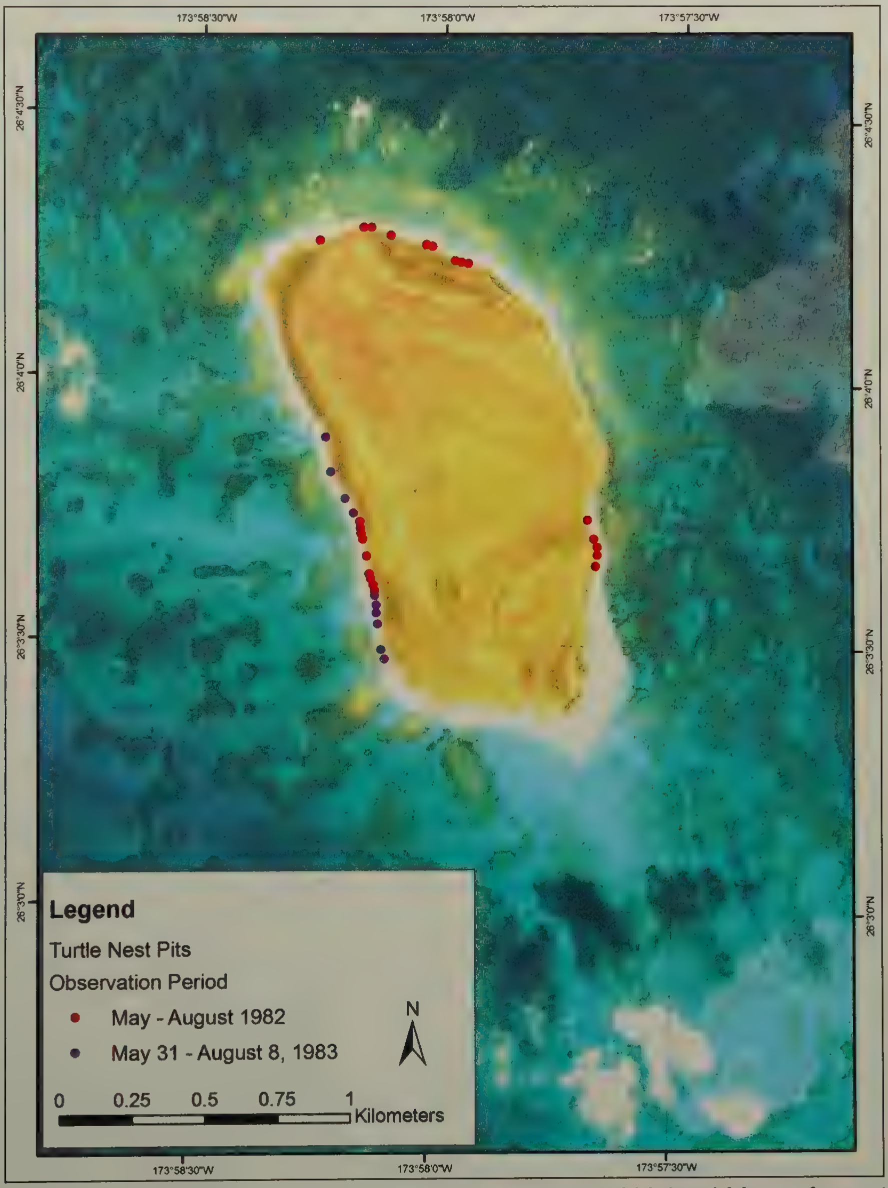


Figure 6.43. Locations of green turtle pits on Lisianski Island May – August 1982 and May – August 1983. Sources: Kam, 1986 and1985.

Pearl and Hermes Atoll

NMFS personnel observed turtle pits and basking green turtles at Pearl and Hermes Atoll (on North, Southeast and Seal Kittery Islands) during parts of the nesting season in some years between 1982 and 2007 (Kam, 1986; Finn et al., 1993; Kubis, 2008). Count data indicate a range of one to 13 pits observed per year, and a mean of 10.0 to 12.6 turtles basking on North and Southeast Islands per day (Table 6.5). Figure 6.44 indicates the locations of pits observed on North and Southeast Islands in 1982.

Midway Atoll

One green turtle nest per year has been found at Midway Atoll since 2006. In 2006, a single nest was located on Spit Island, and in 2007 and 2008 one nest per year was found on Sand Island (J. Klavitter, USFWS, pers. comm.). All three nests (2006, 2007, and 2008) hatched successfully. The nest laid in 2008 was estimated to have contained 89 eggs, 65 of which hatched successfully (J. Klavitter, USFWS, pers. comm.; Figures 6.45 and Figure 6.46). In 2006, NMFS personnel observed 4.5 basking turtles at any one time at Midway Atoll (M. Snover, pers. comm.).

Kure Atoll

Nesting by green turtles has never been observed at Kure Atoll (Kubis, 2008). Biological monitoring and research on other species has been conducted by NMFS and Hawaii Department of Land and Natural Resources personnel at Kure over a period of many years, so it is unlikely that nesting has occurred but has remained unobserved. Green turtles have been observed basking at Kure Atoll in small numbers. In 2006, NMFS personnel observed 0.7 basking turtles at any one time during a total of eight observation days (M. Snover, NMFS, pers. comm.).

Table 6.5. Observations of pits and basking green turtles at Pearl and Hermes Atoll, 1982–2007.

YEAR	DATES	ISLAND	OBSERVATIONS	REFERENCE
1982	5 Jul	North Island	13 pits (Figure 6.44)	Kam (1986)
1982	2 – 5 Jul	Southeast Island	9 pits (Figure 6.44)	Kam (1986)
1982	2 – 6 Jul	North and Southeast	Mean of 10 baskers/day	Kam (1986)
1990	8 – 9 Jun	North Island	2 pits	Finn et al. (1993)
1991	1 Aug – 13 Sep	Southeast Island	1 pit	Finn et al. (1993)
2006	May - Aug	Not specified	12.6 baskers/day	Melissa Snover, NMFS (pers. comm.)
2007	May-Jun	Not specified	Nests observed but not counted	Kubis (2008)

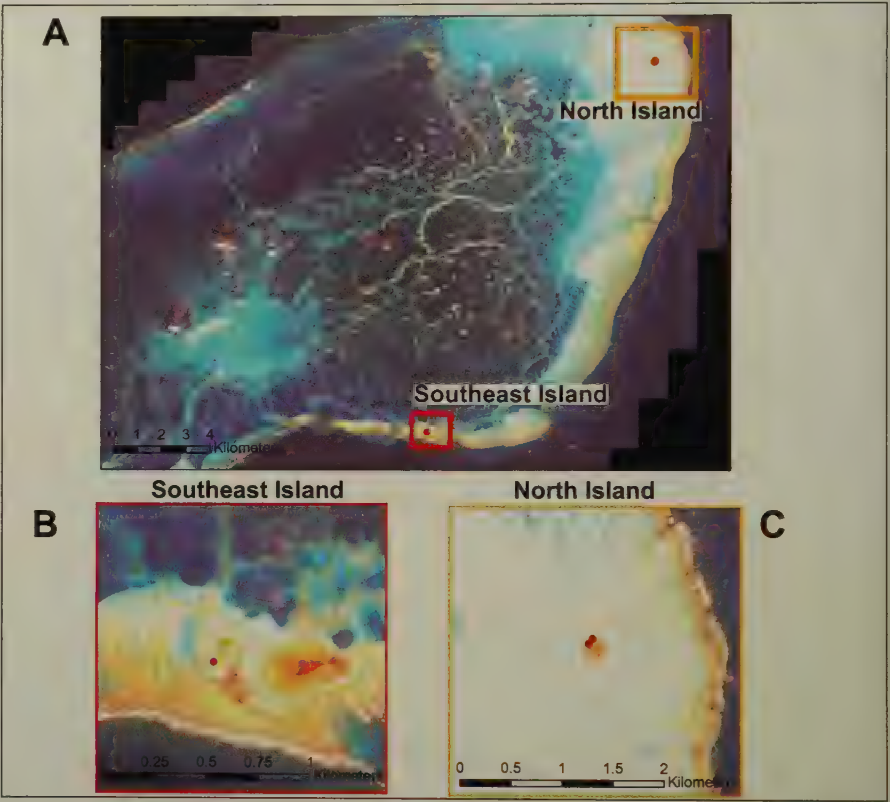


Figure 6.44. Panel A: locations of green turtle pits observed at Pearl and Hermes atoll in 1982. Panel B indicates locations of pits on Southeast Island; panel C indicates pit locations on North Island. Source: Kam, 1986.

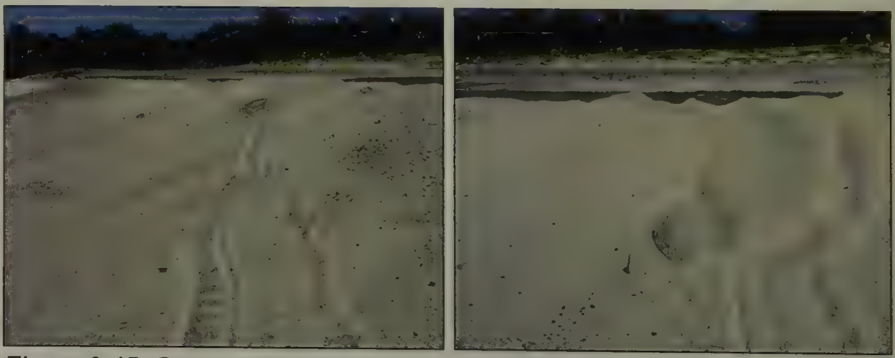


Figure 6.45. Green turtle tracks and nest on Sand Island, Midway Atoll, May 2008. The left panel shows turtle tracks and the right panel shows an active nest. Photos: T. Summers, USFWS.

Conclusions and Management Action

Green turtles have been observed basking at all of the islands and atolls within the Monument, but nesting attempts have been limited to the islands and atolls from French Frigate Shoals to Midway Atoll. As previously described, more than 90% of green turtle nesting occurs at French Frigate Shoals, with a range of approximately 100 to 550 females digging approximately 450 to 2,500 nests each year (Table 6.6). In contrast, between 15 and 91 pits have been observed on Laysan and Lisianski Islands in any one year, 1-13 pits per island at Pearl and Hermes Atoll per year, and only one nest per year at Midway Atoll between 2006 and 2008 (Table 6.5). As the number of nesting females on East Island, French Frigate Shoals has increased over the last three decades, the numbers of nests at Laysan, Lisianski, and Pearl and Hermes Atoll may have also increased over time. Additional periodic counts of pits and/or mark-resighting of nesting females at those locations in future years will help to more precisely estimate the subpopulation sizes of nesting green turtles throughout the Monument.

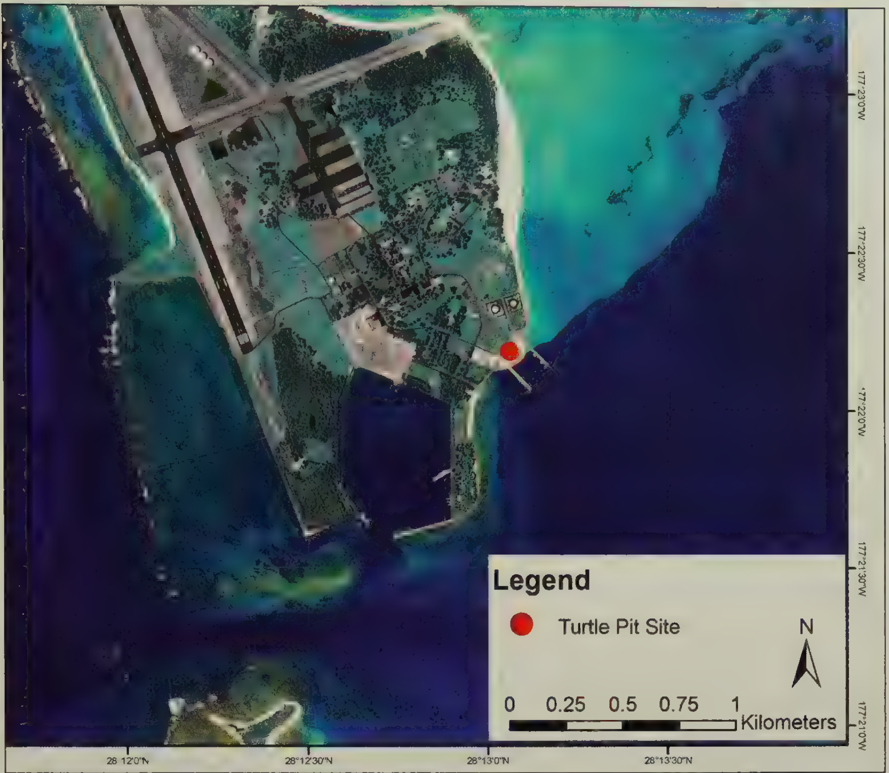


Figure 6.46. Location of green turtle nest on Sand Island, Midway Atoll, in 2008. Source: J. Klavitter; map: K. Keller.

Table 6.6. Numbers of green turtle nest pits observed on all islands and atolls in the NWHI between 1982 and 2008. Dash (-) indicates data not collected or not available; plus sign (+) indicates observed pits but not counted; and zero (0) indicates true count of zero.

ISLAND/ATOLL	1982	1983	1984	1985	1986	1987	1990	1991	2006	2007	2008
Nihoa	0	0	0	0	0	0	0	0	0	0	0
Mokumanamana	0	0	0	0	0	0	0	0	0	0	0
French Frigate Shoals: East Island†	585*	158*	896*	729*	311*	644*	675*	482*	1,904*	1,566*	2,430*
Laysan	45	-	-	-	-	-	-	-	-	50	-
Lisianski	47	19	91	78	15	34	-	-	-	+	-
Pearl and Hermes Atoll: North Island	13	-	-	-	-	-	2	-	-	+	-
Pearl and Hermes Atoll: Southeast Island	9	-	-	-	-	-	-	1	-	+	-
Midway Atoll:	-	-	-	-	-	-	-	-	-	-	-
Spit Island	0	0	0	0	0	0	0	0	1	0	0
Midway Atoll:											
Sand Island	0	0	0	0	0	0	0	0	0	1	1
Kure Atoll	0	0	0	0	0	0	0	0	0	0	0

†Pits have also been observed but not counted in all years on Tern, Trig, Gin and Little Gin Islands at French Frigate Shoals.

*Numbers of pits at East Island, French Frigate Shoals, are estimates based upon numbers of nesting females (Stacy Kubis Hargrove, pers. comm.). Individual turtles lay three to six (mean = 4.5) clutches per season (http://www.fpir.noaa.gov/PRD/prd_green_sea_turtle.html), so estimates of number of nest pits was obtained by multiplying the number of nesting females per year by 4.5.

Papahanaumokuakea Marine National Monument's Draft Management Plan (PMNM, 2008) describes a strategy and three activities to manage green turtle habitat within the Monument, based upon the Recovery Plan for U.S. Pacific Populations of the Green Turtle (*Chelonia mydas*; NMFS and USFWS,1998). Strategy TES-3 of the Monument's Draft Management Plan is to "Ensure that nesting populations of green turtles at source beaches are stable or increasing over the life of the plan" (the life of the plan being 15 years). The first activity planned to achieve this strategy includes the continuation of data collection to monitor nesting turtles on East Island, French Frigate Shoals (with the largest numbers of nesting turtles in the Monument), and the periodic reassessment of the distribution of nesting activity on the other islands and atolls within the NWHI (PMNM, 2008). The second activity to achieve Strategy TES-3 is the protection and management of nesting habitat, including prevention of introduction of mammalian predators such as rats, reduction of artificial light near nesting beaches, prohibition of habitat alteration, and the regulation of human access and activities. Management actions to delay habitat loss due to sea level rise are also advised, but specific activities related to the slowing of climate-change-induced habitat loss are not described (PMNM, 2008). Finally, Strategy TES-3 will be attained by protecting and managing foraging areas and migration routes within the Monument, including identification and mapping of these areas, and management of vessel transit and discharge, and minimization of the introduction of contaminants (PMNM, 2008).

EXISTING DATA GAPS

It is important to develop and regularly update a database of population structure and dynamics for protected species. The database will help managers make effective decisions and determine the effects of previous decisions and events (e.g., climate events, management decisions, research programs, disease outbreaks, etc.). Specific opportunities include research to improve the understanding of:

- The essential habitats and ecological requirements of protected species, to minimize anthropogenic threats and the effect of catastrophic events;
- The diet and foraging behavior of the Hawaiian monk seals throughout different life stages in order to understand the effect of food availability on the population;
- Time budgets, diving, and movement characteristics and energetics of the Hawaiian monk seal, stratified by representative sub-populations, age, and sex classes;
- An appropriate and sensitive assay for biotoxins and metabolites in tissue of monk seals and prey species;
- The effects of climate change on nesting sites of protected species, e.g., the effect of sea level rise on nesting sites of the green sea turtle and Hawaiian monk seal;
- The Allee effect (i.e., that for smaller populations, the reproduction rates and survival of individuals decrease) and thresholds for phase shift;
- Cetacean presence and behavior in the NWHI at different times of the year; and
- The presence/absence of other turtle species and nesting sites at other locations in the NWHI.

REFERENCES

Abernathy, K.J. 1999. Foraging ecology of Hawaiian monk seals at French Frigate Shoals, Hawaii. M.S. Thesis, University of Minnesota, Minneapolis, MN. 65pp.

Abernathy, K. and D.B. Siniff. 1998. Investigations of Hawaiian monk seal, *Monachus schauinslandi*, pelagic habitat use: range and diving behavior. Saltonstall Kennedy Grant Rep. No. NA67FD0058, 30 pp.

Alcorn, D.J., R.J. Forsyth, and R.L. Westlake. 1988. Hawaiian monk seal and green turtle research on Lisianski Island, 1984 and 1985. U.S. Dept. Commerce, NOAA Tech Memo NOAA-TM-NMFS-SWFC-120.

American Cetacean Society. 2003. Fact Sheet: Orca (Killer Whale) /Orcinus orca. /http://www.acsonline.org/factpack/KillerWhale.htm.

Amerson, A.B. Jr. 1971. The Natural History of French Frigate Shoals, Northwestern Hawaiian Islands. Atoll Research Bulletin 150.

Amerson, A.B., Jr., R.B. Clapp, and W.O. Wirtz III. 1974. The natural history of Pearl and Hermes Reef, Northwestern Hawaiian Islands. Atoll Research Bulletin 174, 347 pp.

Andrews, K.R., L. Karczmarski, W.W.L. Au, S.H. Rickards, C.A. Vanderlip, and R.J. Toonen. 2006. Patterns of genetic diversity of the Hawaiian spinner dolphin (*Stenella longirostris*). Atoll Research Bulletin 543: 65-73.

Anotnelis, G. A., J.D. Baker, T.C. Johanos, R.C. Braun, and A.L. Hartig, 2006. "Hawaiian Monk Seal (*Monachus schauinslandi*): Status and Conservation Issues", The Atoll Research Bulletin No. 543, pp. 75-101. Ed. Macintyre, I.G. Northwestern Hawaiian Islands Third Scientific Symposium. November 2-4, 2004, National Museum of Natural History. Smithsonian Institution, Washington, DC. USA.

Baird, R.W., A.M. Gorgone, D.J. McSweeney, A.D. Ligon, M.H. Deakos, D.L. Webster, G.S. Schorr, K.K. Martien, D.R. Salden, and S.D. Mahaffy. In Press a. Population structure of island-associated dolphins: evidence from photo-identification of common bottlenose dolphins (*Tursiops truncatus*) in the main Hawaiian Islands. Marine Mammal Science.

Baird, R.W., A.M. Gorgone, D.J. McSweeney, D.L. Webster, D.R. Salden, M.H. Deakos, A.D. Ligon, G.S. Schorr, J. Barlow, and S.D. Mahaffy. 2008. False killer whales (*Pseudorca crassidens*) around the main Hawaiian Islands: Long-term site fidelity, inter-island movements, and association patterns. Marine Mammal Science 24(3):591-612.

Baird, R.W., D.J. McSweeney, C. Bane, J. Barlow, D.R. Salden, L.K. Antoine, R.G. LeDuc, and D.L. Webster. 2005b. Killer whales in Hawaiian waters: information on population identity and feeding habits. Pacific Science 60(4): 523-530.

Baird, R.W., D.J. McSweeney, D.L. Webster, A.M. Gorgone, and A.D. Ligon. 2003. Studies of odontocete population structure in Hawaiian waters: results of a survey through the main Hawaiian Islands in May and June 2003. National Oceanic and Atmospheric Administration Report No. AB133F-02-CN-0106.

Baird, R.W., G.S. Schorr, D.L. Webster, S.D. Mahaffy, A.B. Douglas, A.M. Gorgone, and D.J. McSweeney. 2006. A survey for odontocete cetaceans off Kauai and Niihau, Hawai'i, during October and November 2005: Evidence for population structure and site fidelity. Pacific Islands Fisheries Science Center Report No. AB1333F05SE5197.

Baird, R.W., D.L. Webster, S.D. Mahaffy, D.J. McSweeney, G.S. Schorr, and A.D. Ligon. In Press,b. Site fidelity and association patterns in a deep-water dolphin: Rough-toothed dolphins (*Steno bredanensis*) in the Hawaiian Archipelago. Marine Mammal Science.

Baird, R.W., D.L. Webster, and D.J. McSweeney. 2005a. Biases and data limitations of odontocete cetacean sighting data from small-boat based surveys around the main Hawaiian Islands. Cascadia Research Collective. Report prepared under Purchase Order No. N62742-05-P-1880 from NOAA Fisheries Office of Protected Resources.

Baker, J.D. 2004. Evaluation of closed capture-recapture methods to estimate abundance of Hawaiian monk seals. Ecological Applications, 14(4): 987-998.

Baker, J.D., A.L. Harting, and T.C. Johanos. 2006. Use of discovery curves to assess abundance of Hawaiian monk seals. Marine Mammal Science 22: 847-861

Baker, J.D. and T.C. Johanos. 2004. Abundance of the Hawaiian monk seal in the main Hawaiian Islands. Biological Conservation 116: 103-110.

Balazs, G.H. 1976. Green turtle migrations in the Hawaiian Archipelago. Biological Conservation 9: 125-140.

Balazs, G.H. 1980. Synopsis of biological data on the green turtle in the Hawaiian Islands. NOAA-TM-NMFS-SWFS-7.

Balazs, G.H. and M. Chaloupka. 2004. Thirty-year recovery trend in the once depleted Hawaiian green turtle stock. Biological Conservation 117: 491-498.

Balazs, G.H. and M. Chaloupka. 2006. Recovery trend over 32 years at the Hawaiian green sea turtle rookery of French Frigate Shoals. Atoll Research Bulletin 543: 147-158.

Barlow, J. 2006. Cetacean abundance in Hawaiian waters estimated from a summer/fall survey in 2002. Marine Mammal Science 22(2): 446-464.

Barlow, J. and S.D. Mahaffy. 2008. False killer whales (*Pseudorca crassidens*) around the main Hawaiian Islands: Long-term site fidelity, inter-island movements, and association patterns. Marine Mammal Science 24(3): 591-612.

Barlow, J. and S. Rankin. 2007. False killer whale abundance and density: preliminary estimates for the PICEAS study area south of Hawaii and new estimates for the US EEZ around Hawaii. Administrative Report LJ-07-02.

Barlow, J., S. Rankin, E. Zele, and J. Appler. 2004. Marine mammal data collected during the Hawaiian Islands cetacean and ecosystem assessment survey (HICEAS) conducted aboard the NOAA ships McArthur and David Starr Jordan, July-December 2002. NOAA Technical Memorandum, NOAA-TM-NMFS-SWFSC-362. 47 pp.

Calambokidis, J., E.A. Falcone, T.J. Quinn, A.M. Burdin, P.J. Clapham, J.K.B. Ford, C.M. Gabriele, R. LeDuc, D. Mattila, L. Rojas-Bracho, J.M. Straley, B.L. Taylor, J. Urban R., D. Weller, B.H. Witteveen, M. Yamaguchi, A. Bendlin, D. Camacho, K. Flynn, A. Havron, J. Huggins, and N. Maloney. 2008. SPLASH: Structure of Populations, Levels of Abundance and Status of Humpback Whales in the North Pacific. Final report for the U.S. Department of Commerce, contract AB133F-03-RP-00078. 57 pp.

Carretta,, J.V., K.A. Forney, M.M. Muto, J. Barlow, J. Baker, B. Hanson, and M.S. Lowry. 2005. Draft U.S. pacific Marine Mammal Stock Assessments: 2005. NOAA-TM-NMFS-SWFSC Technical Memorandum. 80 pp.

Chivers, S.J., R.W. Baird, D.J. McSweeney, D.L. Webster, N.M. Hedrick, and J.C. Salinas. 2007. Genetic variation and evidence for population structure in eastern North Pacific false killer whales (*Pseudorcacrassidens*). Canadian Journal of Zoology 85: 783-794.

Craig, M.P. and T.J. Ragen. 1999. Body size, survival, and decline of juvenile Hawaiian monk seals, *Monachus schauinslandi*. Marine. Mammal Science. 15(3): 786-809

Dizon, A.E. and G.H. Balazs. 1982. Radio telemetry of Hawaiian green turtles at their breeding colony. Marine Fisheries Review 44: 13-20.

Ebhherhardt, L.L, R.A. Garrott, and B.L. Becker. 1999. Using trend indicies for endangered species. Marine Mammal Science. 15(3): 776-785.

Finn, M., J.R. Henderson, B.L. Becker, and T.J. Ragen. 1993. The Hawaiian monk seal and green turtle at Pearl and Hermes Reef, 1990-1991. U.S. Dept. Commerce, NOAA Tech Memo NOAA-TM-NMFS-SWFC 182.

Finn, M. A., and M. A. Rice. 1994. Hawaiian monk seal observations at Necker Island, 1993. ‘Elepaio 55:7-10.

Fyler, C.A., T.W. Reeder, A. Berta, G. Antonelis, A. Aguilar, and E. Androukaki. 2005. Historical biogeography and phylogeny of monachine seals (*Pinnipedia: Phocidae*) based on mitochondrial and nuclear DNA data. Journal of Biogeography 32, 1267-1279.

Galbreath, E.C. 1963. Three beaked whales stranded on Midway Islands, central Pacific Ocean. Journal of Mammalogy 44: 422-423.

Galver, L. 2002. The molecular ecology of spinner dolphins, *Stenella longirostris*: genetic diversity and population structure. PhD Thesis, Sripps Institute of Oceanography, San Diego, California.

Gerrodette, T.M. and W.G. Gilmartin. 1990. Demographic consequences of changed pupping and hauling sites of the Hawaiian monk seal. Conservation Biology 4: 423-430.

Gilmartin, W.G., R.J. Morrow, and A.M. Houtman. 1986. Hawaiian monk seal observations and captive maintenance project at Kure Atoll, 1981. U.S. Dep. Commer., NOAA Tech. Memo. NOAA-TM-NMFS-SWFC-59. 9 pp.

Goodman-Lowe, G.D. 1998. Diet of the Hawaiian monk seal (*Monachus schauinslandi*) from the Northwestern Hawaiian Islands during 1991-1994. Marine Biology 132: 535-546.

Harting, A.L. 2002. Stochastic simulation model for the Hawaiian monk seal. Ph.D. Dissertation. Montana State University, Bozeman, MT. 328 pp.

Harting, A.L., J.D. Baker, and T.C Johanos. 2007. Reproductive Patterns of the Hawiian Monk Seal. Marine Mammal Science 23(3): 553-573.

Herman, L.M. and R.C. Antinoja. 1977. Humpback whales in the Hawaiian breeding waters: population and pod characteristics. Scientific Report for the Whale Research Institute No. 29: 59-85.

Herman, L.M., P.H. Forestell, and R.C. Antinoja. 1980. The 1976/77 migration of humpback whales into Hawaiian waters: composite description. Report to the U.S. Marine Mammal Commision, No. MMC-77/19. 62 pp.

Johanos, T.C. and T.J. Ragen. 1999. The Hawaiian monk seal in the Northwestern Hawaiian Islands, 1997. NOAA-TM-NMFS-SWFSC-262.

Johanos, T.C. and R.P. Withrow. 1988. Hawaiian monk seal and green turtle research on Lisianski Island, 1987. U.S. Dept. Commerce, NOAA Tech Memo NOAA-TM-NMFS-SWFC-121.

Johnson, A.M., R.L. DeLong, C.H. Fiscus, and K. Kenyon. 1982. Population status of the Hawaiian monk seal (*Monachus schauinslandi*), 1978. Journal of Mammology 63(3): 415-421.

Johnston, D.W., M.E. Chapla, L.E. Williams, and D.K. Mattila. 2007. Identification of humpback whale *Megaptera novaeangliae* wintering habitat in the Northwestern Hawaiian Islands using spatial habitat modeling. Endangered Species Research 3: 249-257.

Kam, A.K.H. 1985. Green turtle research on Lisianski Island, 1983. Southwest Fisheries Science Center Admin. Report H-85-11.

Kam, A.K.H. 1986. The green turtle, *Chelonia mydas*, at Laysan Island, Lisianski Island, and Pearl and Hermes Reef, summer 1982. U.S. Dept. Commerce, NOAA Tech Memo NOAA-TM-NMFS-SWFS-65.

Karczmarski, L., G. Ross, B. Würsig, and B. Winning. 1999. Ecological studies of Hawaiian spinner dolphins, *Stenella longirostris*, in Midway Atoll, Central Pacific. Unpublished report to U.S. Fish and Wildlife Service and National Marine Fisheries Service. 22 pp.

Karczmarski, L., B. Wursig, G. Gailey, K.W. Larson, and C. Vanderlip. 2005. Spinner dolphins in a remote Hawaiian atoll: Social grouping and population structure. Behavioral Ecology 16(4): 675-685.

Karczmarski, L., B. Würsig, and B. Winning. 1998. Socio-ecology and population biology of spinner dolphins, *Stenella longirostris*, in Midway Atoll, Northwest Hawaiian Chain, Central Pacific. Unpublished report to U.S. Fish and Wildlife Service and National Marine Fisheries Service. 41 pp.

Kenyon, K.W. 1972. Man versus the monk seal. Journal of Mammology 53(4): 687-696.

Kenyon, K. W. 1973. The Hawaiian monk seal. International Union for the Conservation of Nature and Natural Resources, Publications, New Series, Supplemental Paper 29: 88-97.

Kenyon, K.W. 1977. Caribbean monk seal extinct. Journal of Mammalogy 58: 97-98.

Kenyon , K.W., and D.W. Rice. 1959. Life history of the Hawaiian monk seal. Pacific Science 31: 215-252.

Kubis, S.A. 2008. NWHI Green turtle activity survey May 18 – June 4, 2007: A record of observations made during OES-0704. PIFSC Internal Report IR-08-024.

Leatherwood, S., R.R. Reeves, W.F. Perrin, and W.E. Evans. 1982. Whales, dolphins, and porpoises of the eastern North Pacific and adjacent Arctic waters: A guide to their identification. NOAA Technical Report. NMFS Circular 444. 243 pp.

Maldini, D., L. Mazzuca, and S. Atkinson, S. 2005. Odontocete stranding patterns in the Main Hawaiian Islands (1937-2002): How do they compare with live animal surveys? Pacific Science 59(1): 55-67.

McDonald, M. A., and C. G. Fox. 1999. Passive acoustic methods applied to fin whale population density estimation. Journal of the Acoustical Society of America 105: 2643-2651.

McSweeney, D.J., R.W. Baird, and S.D. Mahaffy. 2007. Site fidelity, associations and movements of Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales off the island of Hawaii. Marine Mammal Science 23: 666-687.

McSweeney, D.J., R.W. Baird, S.D. Mahffy, D.L. Webster, and G.S. Schorr. In Press. Site fidelity and association patterns of a rare species: pygmy killer whales (*Feresa attenuata*) in the main Hawaiian Islands. Marine Mammal Science.

Mobley, J.R., L. Mazzuca, A.S. Craig, M.W. Newcomer, and S.S. Spitz. 2001. Killer Whales (*Orcinus orca*) Sighted West of Ni'ihau, Hawaii. Pacific Science 55(3): 301-303.

Mobley, J. R., Jr., M. Smultea, T. Norris, and D. Weller. 1996. Fin whale sighting north of Kauai, Hawaii. Pacific Science 50: 230-233.

Mobley, J.R. Jr., S.S. Spitz, K.A. Forney, R. Grotenfendt, and P.H. Forestell. 2000. Distribution and abundance of *Odontocete* species in Hawaiian waters: preliminary results of 1993-98 aerial surveys. Administrative Report LJ-00-14C. NOAA Southwest Fisheries Science Center, La Jolla, CA. 26 pp.

Morrow, R.J. and E.K. Buelna. 1985. The Hawaiian monk seal and green turtle on Necker Island, 1983. U.S. Dept. Commerce, NOAA Tech Memo NOAA-TM-NMFS-SWFC-55.

National Marine Fisheries Service and U.S. Fish and Wildlife Service. 1998. Recovery Plan for U.S. Pacific Populations of the Green Turtle (*Chelonia mydas*). National Marine Fisheries Service, Silver Spring, MD.

National Marine Fisheries Service. 2007. Recovery Plan for the Hawaiian Monk Seal (*Monachus sshauinslandi*). Second Revision. National Marine Fisheries Service, Silver Spring, MD. 165 pp.

Niethammer, K.R., G.H. Balazs, J.S. Hatfield, L. Nakai, and J.L. Megyesi. 1997. Reproductive biology of the green turtle (*Chelonia mydas*) at Tern Island, French Frigate Shoals, Hawaii. Pacific Science 51: 36-47.

Nitta, E. 1991. The marine mammal stranding network for Hawaii: an overview. In: J.E. Reynolds III, D.K. Odell (eds.), Marine Mammal Strandings in the United States, pp.56-62. NOAA Tech. Rep. NMFS 98. 157 pp.

Nitta, E. and J.R. Henderson. 1993. A review of interactions between Hawaii's fisheries and protected species. Marine Fisheries Review 55(2): 83-92.

Norris, K.S. and T.P. Dohl. 1980. The structure and functions of cetacean schools. Pp: 211-261. In: Cetacean behavior: mechanisms and functions (ed. L.M. Herman). John Wiley and Sons: New York.

Papahanaumokuakea Marine National Monument. 2008. Papahanaumokuakea Marine National Monument Draft Management Plan.

Parrish, F.A., G.J. Marshall, C.L. Littnan, M. Heithaus, S. Canja, B.L. Becker, R.C. Braun, and G.A. Antonelis. 2005. Foraging of juvenile monk seals at French Frigate Shoals, Hawaii. Marine Mammal Science 21(1):93-107.

Parrish, F.A. and K. Abernathy. 2006. Movements of monk seals relative to ecological depth zones in the lower Northwestern Hawaiian Islands. Atoll Res. Bull. 543: 115-130

Parrish, F.A., K. Abernathy, G.J. Marshall, and B.M. Buhleier. 2002. Hawaiian monk seals (*Monachus schauinslandi*) foraging in deepwater coral beds. Marine Mammal Science 18: 244-258.

Parrish, F.A., M.P. Craig, T.J. Ragen, G.J. Marshall, and B.M. Huhleier. 2000 Identifying diurnal foraging habitat of endangered Hawaiian monk seals using a seal-mounted video camera. Marine Mammal Science 16: 392-412.

Payne, K.J., C. Turner, and C.P. Malachowski.2007.Trip Report: Laysan Island 15 March 2007 to 24 September 2007. U.S. Fish and Wildlife Service, Honolulu, Hawaii.

Perrin, W.F., B. Wursig, and J.G.M. Thewissen. (eds.). 2002. Encyclopedia of Marine Mammals. Academic Press, New York. 1414 pp.

Polovina, J.J., G.T. Mitchum, N.E. Graham, M.P. Craig, E.E. DeMartini, and E.N. Flint. 1994. Physical and biological consequences of a climate event in the central North Pacific. Fish. Oceanogr. 3(1): 15-21

Ragen, T.J. 1999. Human activities affecting the population trends of the Hawiian monk seal. Pp: 183-194. In: Musick, J.A. (Ed.), Life in the slow land: Ecology and conservation of long-lived marine animals. American Fisheries Society Symposium 23, American Fisheries Society, Bethesda.

Ragen, T.J. and M.A. Finn. 1996. The Hawaiian monk seal on Necker and Nihoa Islands, 1993. Pp: 89-104. In: T.C. Johanos and T.J. Ragen (ed.), The Hawaiian monk seal in the Northwestern Hawaiian Islands, 1993. U.S. Dep. Commer. NOAA Tech. Memo. NMFS-SWFSC-227, 141p.

Reeves, R.R., B.S. Stewart, P.J. Clapham, and J.A. Powell. 2002. National Audubon Society Guide to Marine Mammals of the World. Chanticleer Press, Inc., New York. 526 pp.

Repenning, C.A., C.X.E. Ray, and D. Grigorescu. 1979. Pinniped biogeography. Pp: 357-369. In: J.Gray and A.J. Boucet, eds., Historical biogeography, plate tectonics and the changing environment. Oregon State University Press

Rice, D.W. 1960. Distribution of the bottle-nosed dolphin in leeward Hawaiian Islands. Journal of Mammalogy 41(3): 407-408.

Rice, D.W. 1960. Population dynamics of the Hawaiian monk seal. Journal of Mammology 41:376-385.

Rickards, S.H., C. Vanderlip, and G. Oliver. 2001. Spinner dolphins (*Stenella longirostris*) of Midway Atoll, Northwest Hawaiian Archipelago: February - November 2001. Year-end report to National Marine Fisheries Service and U.S. Fish and Wildlife Service. 50 pp.

Ridgway, S.H. and R. Harrison, Sir. (Eds.). 1994. Handbook of Marine Mammals, Volume 5: The First Book of Dolphins. Academic Press, London. 416 pp.

Ridgway, S.H. and R. Harrison, Sir (Eds.). 1999. Handbook of Marine Mammals, Volume 6: The Second Book of Dolphins and Porpoises. Academic Press, San Diego. 486 pp.

Rountree, V., J. Darling, G. Silber, and M. Ferrari. 1980. Rare sighting of a right whale (*Eubalaena glacialis*) in Hawaii. Canadian Journal of Zoology 58 :209-312.

Shallenberger, E.W. 1977. Humpback whales in Hawaii: population and distribution. Marine Technical Society.

Shallenberger, E.W. 1981. The status of Hawaiian cetaceans. Report to the Marine Mammal Commission, No. MMC-77/23. 79 pp.

Schorr, G.S., R.W. Baird, M.B. Hanson, D.L. Webster, D.J. McSweeney, and R.D. Andrews. In press. Movements of the first satellite-tagged Cuvier's and Blaineville's beaked whales in Hawaii. Marine Mammal Science

Stewart, B.S. 2004a. Geographic patterns of foraging dispersion of Hawaiian monk seals (*Monachus schauinslandi*) at the Northwestern Hawaiian Islands. Pacific Islands Fisheries Science Center Admin. Rep. H-04-05C.

Stewart, B.S. 2004b. Foraging ecology of Hawiian monk seals (*Monachus schauinslandi*) at Pearl and Hermes Reef, Northwestern Hawaiian Islands: 2000 and 2001. Pacific Islands Fisheries Science Center Admin. Rep. H-04-03C.

Stewart B.S., G.A. Antonelis, J.D. Baker, and P.K. Yochem 2006. Foraging biogeography of Hawaiian monk seals in the Northwestern Hawaiian Islands. Atoll Research. Bulletin. 543: 131-145

Stewart, B.S. and P.K. Yochem. 2004a. Dispersion and foraging of Hawaiian monk seals (*Monachus schauinslandi*) near Lisianski and Midway Islands: 2000-2001. Pacific Islands Fisheries Science Center Admin. Rep. H-04-04C

Stewart, B.S. and P.K. Yochem. 2004b Use of marine habitats by Hawaiian monk seals (*Monachus schauinslandi*) from Laysan Island: Satellite-linked monitoring in 2001-2002. Pacific Islands Fisheries Science Center Admin. Rep. H-04-02C.

Stewart, B.S. and P.K. Yochem. 2004c Use of marine habitats by Hawaiian monk seals (*Monachus schauinslandi*) from Kure Atoll: Satellite-linked monitoring in 2001-2002. Pacific Islands Fisheries Science Center Admin. Rep. H-04-02C

Thompson, P.O. and W.A. Friedl. 1982. A long term study of low frequency sound from several species of whales off Oahu, Hawaii. Cetology 45: 1-19.

Tomich, P.Q. 1986. Mammals in Hawaii. Bishop Museum Press, Honolulu. 375 pp.

Townsend, C.H. 1935. The distribution of certain whales as shown by logbook records of American whale ships. Zoologica 19(1): 1-50, 4 charts.

Wade, P.R. and R.P. Angliss. 1997. Guidelines for assessing marine mammal stocks: report of the GAMMS workshop, April 3-5, 1996, Seattle, Washington. U.S. Department of Commerce, NOAA Tech. Memo. NMFS-OPR-12. 93pp.

Westlake, R.L. and W.G. Gilmartin. 1990. Hawaiian monk seal pupping locations in the Northwestern Hawaiian Islands. Pacific Science 44: 366-383.

Westlake, R.L. and P.J. Siepmann. 1988. Hawaiian monk seal and green turtle research on Lisianski Island, 1986. U.S. Dept. Commerce NOAA Tech Memo NOAA-TM-NMFS-SWFS-119.

Wetherall, J.A. G.H. Balazs, and M.Y.Y. Yong. 1998. Statistical methods for green turtle nesting surveys in the Hawaiian Islands. Pp: 278-280. In: Epperly, S.P., and J. Braun (Eds.), Proceedings of the 17th Annual Symposium on Sea Turtle Biology and Conservation. NOAA Technical Memorandum, NMFS-SEFSC-415.

Wirtz, W.O. II. 1968. Reproduction, growth and development, and juvenile mortality in the Hawaiian monk seal. Journal of Mammology 49:229-238.

Woodward, P.W. 1972. The natural history of Kure Atoll, Northwestern Hawaiian Islands. Atoll Research Bulletin 164. 338 pp.

PERSONAL COMMUNICATIONS

Baird, R.W. Cascadia Research, Olympia, WA, USA.

Becker, B. National Marine Fisheries Service. Honolulu, HI, USA.

Klavitter, J. U.S. Fish and Wildlife Service, Honolulu, HI, USA.

Kubis Hargrove, S. National Marine Fisheries Service. Honolulu, HI, USA.

Rehkemper, C. U.S. Fish and Wildlife Service, Honolulu, HI, USA.

Snover, M. National Marine Fisheries Service. Honolulu, HI, USA.

Summers, T. U.S. Fish and Wildlife Service, Honolulu, HI, USA.

WEBSITES

NOAA. http://www.nmfs.noaa.gov/pr/species/esa/mammals.htm

NOAA. http://www.nmfs.noaa.gov/pr/species/turtles/

Wildlife Conservation Society. http://www.wcs.org/sw-high_tech_tools/landscapeecology/townsend_charts

NOAA. http://www.fpir.noaa.gov/PRD/prd_green_sea_turtle.html

Seabirds

Kaylene E. Keller[1], Angela D. Anders[2], Scott A. Shaffer[3], Michelle A. Kappes[3], Beth Flint[4] and Alan Friedlander[5,6]

INTRODUCTION

The Northwestern Hawaiian Islands (NWHI) provide habitat for an estimated 5.5 million nesting seabirds representing 22 different species (see Figures 7.1 and 7.2 and Fefer et al., 1984). For many of these species, the Monument provides the majority of available nesting habitat. Nesting occurs throughout the year, varying by species and within species, and by annual food availability (Harrison, 1990). The largest breeding populations occur at Midway Atoll, Laysan Island and Nihoa (USFWS, 2005). While the Monument protects seabird breeding and nesting habitat, the foraging ranges for most of these species extend beyond the Monument's boundaries, with foraging distances ranging from 3 km to several thousand kilometers (e.g., Fernández et al., 2001). Some seabird species occur year-round in the Monument, while others migrate to other parts of the Pacific when not breeding. Juvenile birds may also remain at sea for several years before returning to their breeding colonies inside Monument water. Overall, the NWHI provide high-quality breeding habitat, with low predation risk and low disturbance conditions (Table 7.1).

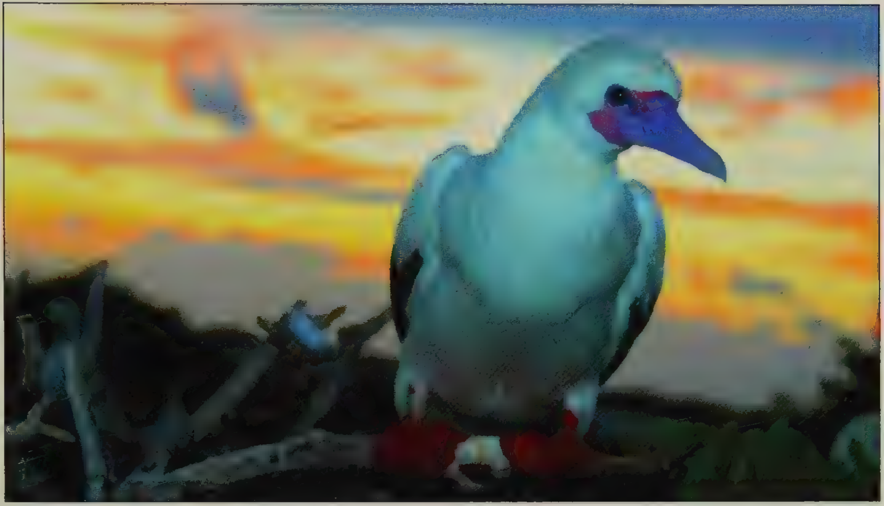


Figure 7.1. A Red-footed Booby. Red-footed Boobies nest on all islands and atolls in the NWHI. Photo: J. Watt.

Figure 7.2. Brown Noddy Terns and Brown Boobies at Pearl and Hermes Atoll. Photo J. Watt.

The distribution of seabirds within the Monument reflects, to some extent, the nesting habitat currently available on the islands (Tables 7.2 and 7.3). Nesting distribution has also been affected by human disturbance in the late 19th and 20th centuries, including egg and feather hunting, and destruction of habitat due to military activities during and after World War II. For example, populations of many of the seabird species on Laysan Island are likely still recovering after the devegetation of the island by guano miners and hunter-introduced feral rabbits in the early 1900s (Ely and Clapp, 1973). Further habitat losses have occurred from the introduction of non-native plants like golden crown-beard (*Verbisena* encelioides) and rodent pests like rats and mice. Numbers of nesting adults of some species are also still increasing on Tern and East Islands at French Frigate Shoals after the decommissioning of Naval and Coast Guard stations following World War II (Amerson, 1971).

---

1. NOAA/NOS/ONMS/Papahanaumokuakea Marine National Monument
2. Clancy Environmental Consultants, Inc.
3. University of California Santa Cruz
4. U.S. Fish and Wildlife Service
5. NOAA/NOS/NCCOS/CCMA Biogeography Branch
6. The Oceanic Institute

Table 7.1. Life history and management Information for selected seabirds of the NWHI. Source: USFWS, unpub. data.

				BREEDING PERIOD								FEEDING BEHAVIOR		ESTIMATED FORAGING RANGE FROM COLONIES	
Common Name	Protection Status	IUCN	ESA	Primary Months of Presence	Months When Breeding		Fish	Fish Eggs	Cephaopods (squid, octopus)	Ephausiids (krill)	Crustaceans	Feeding Habits	Feeding Activity	Distance	Source
					Eggs	Chicks									
Procellariiformes (Albatrosses, Petrels and Shearwaters)															
Laysan Albatross	Highly Imperiled and High Concern	VU A4bd		Nov - Jul	Nov-Feb	Jan-Jul	X	X	X			Surface feeding	Nocturnal	1,000 km	
Black-footed Albatross	Highly Imperiled and High Concern	EN A3bd		Oct - Jul	Oct-Feb	Jan-Jul	X	X	X			Surface feeding	Diurnal	700 km	
Short-tailed Albatross		VU D2	Endangered	Nov - Feb	Oct-Jan	Jan-Jun	X	X	X			Surface feeding	Diurnal	Unknown	
Bonin Petrel	Moderate Concern	LC		Aug - Jun	Jan-March	Feb-Jun	X		X		X	Surface feeding	Nocturnal	Unknown	
Bulwer's Petrel	Moderate Concern	LC		Apr - Oct	May-Jul	Jul-Oct	X	X	X		X	Surface feeding	Nocturnal	Unknown	
Wedge-tailed Shearwater	Low or Not Currently at Risk	LC		May - Dec	May-Aug	Aug-Dec	X		X			Contact dipping / associated with large predatory fish	Diurnal	480 km	
Christmas Shearwater	Highly Imperiled and High Concern	LC		Feb - Oct	April-Jul	Jun-Oct	X		X			Contact dipping and pursuit plunging / associated with large predatory fish	Nocturnal	Unknown	
Tristram's Storm-Petrel	Highly Imperiled and High Concern	NT		Oct - May	Dec-Feb	Feb-May	X		X			Surface feeding	Nocturnal	Unknown	
Pelecaniformes (Tropicbirds, Boobies and Frigatebirds)															
Red-footed Booby	Low or Not Currently at Risk	LC		Jan - Dec	Jan - Aug	Mar - Dec	X		X			Plunge diving / associated with large predatory fish	Diurnal	276 km	Flint
Masked Booby	Moderate Concern	LC		Dec - Oct	Jan - Jul	Mar - Oct	X		X			Plunge diving / associated with large predatory fish	Diurnal	158 km	Flint
Brown Booby	Moderate Concern	LC		Jan - Oct	Feb - Aug	April - Oct	X		X			Plunge diving / associated with large predatory fish	Diurnal	80 km	USFWS, 2005
Great Frigatebird	Moderate Concern	LC		Jan - Dec	Feb - Jul	April - Nov	X		X			Surface feeding / associated with large predatory fish	Diurnal	612 km	Weimerskirch et al., 2004

Table 7.1 (Continued). Life history and management Information for selected seabirds of the NWHI. Source: USFWS, unpub. data.

				BREEDING PERIOD							FEEDING BEHAVIOR		ESTIMATED FORAGING RANGE FROM COLONIES	
Common Name	Protection Status	IUCN	ESA	Primary Months of Presence	Months When Breeding		Fish	Fish Eggs	Cephalopoda (squid, octopus)	Euphausiids (krill)	Crustaceans	Feeding Habits	Feeding Activity	Distance	Source
					Eggs	Chicks									
Lesser Frigatebird		LC		Feb - Jul	Feb - Jul		X		X			Surface feeding / associated with large predatory fish	Diurnal	Unknown	
Red-tailed Tropicbird	Moderate Concern	LC		Feb - Nov	Mar - Aug	April - Nov	X		X			Plunge diving	Diurnal	468 km	Flint
White-tailed Tropicbird		LC		Jan - Dec	Jan - Dec	Jan - Dec	X		X			Plunge diving	Diurnal	374 km	Flint
Charadriiformes (Terns and Noddies)															
Black Noddy	Moderate Concern	LC		year-around	Nov - Jun	Dec - Aug	X		X		X	Surface feeding / associated with large predatory fish	Diurnal	80 km	USFWS, 2005
Brown Noddy	Low or Not Currently at Risk	LC		year-around	Jan - Oct	Feb - Nov	X		X			Surface feeding / associated with large predatory fish	Diurnal	163 km	Flint
Blue Noddy	Highly Imperiled and High Concern	LC		year-around	Jan - May	Jan - Jun	X					Surface feeding	Diurnal	Near-shore	
White Tern	Moderate Concern	LC		year-around	Jan - Dec	Jan - Dec	X		X			Surface feeding / associated with large predatory fish	Diurnal	Near-shore	
Sooty Tern	Moderate Concern	LC		Mar - Sep	Mar - Jul	April - Sep	X		X			Surface feeding / associated with large predatory fish	Primarily nocturnal	740 km	Flint, 1991
Gray-backed Tern	Moderate Concern	LC		Feb - Oct	Feb - Aug	April - Oct	X		X	X	X	Surface feeding / associated with large predatory fish	Diurnal	370 km	USFWS, 2005
Little Tern	Moderate Concern	LC		Feb - Oct	Feb - Aug	April - Oct	X				X	Plunge diving	Diurnal	3 km	USFWS, 2005

Table 7.2. Seabird nesting distribution in the NWHI. Source: USFWS, unpub. data.

	NIHOA ISLAND	MOKU-MANA-MANA	FRENCH FRIGATE SHOALS									GARDNER PINNA-CLES	MARO REEF	LAYSAN ISLAND	LISIANSKI ISLAND	PEARL AND HERMES ATOLL						MIDWAY ATOLL			KURE ATOLL	
			Disappearing Island	Little Gin Island	Gin Island	Le Perouse Pinnacle	East Island	Round Island	Shark Island	Tern Island	Trig Island					Seal Kittery Island	Grass Island	Southeast Island	Bird Island	Little North Island	North Island	Spit Island	Eastern Island	Sand Island	Sand Island	Green Island
Black-footed Albatross	X	X		X	X		X			X	X	X		X	X	X	X	X		X	X	X	X	X		X
Laysan Albatross	X	X		X	X		X			X	X	X		X	X	X	X	X		X	X	X	X	X		X
Short-tailed Albatross																										
Bonin Petrel							X			X		?		X	X	X	X	X					X	X		X
Bulwer's Petrel	X	X				X	X			X				X	X			X						X		
Wedge-tailed Shearwater	X	X					X			X		X		X	X	X	X	X					X	X		X
Christmas Shearwater	X	?					X			X				X	X	X	X					?	X			X
Tristram's Storm-Petrel	X	X				X	X			X				X	?			X						X		
Red-tailed Tropicbird	X	X					X			X		X		X	X	X	X	X			X	X	X	X		X
White-tailed Tropicbird																								X		
Masked Booby	X	X		X	X	X	X			X	X	X		X	X	X	X	X		X	X	X	X			X
Brown Booby	X	X				X						X		X	X	X	X	X			X	?	X			X
Red-footed Booby	X	X				X	X			X		?		X	X	X	X	X			X	X	X			X
Great Frigatebird	X	X					X			X				X	X	X	X	X			X	?	X			
Lesser Frigate Bird										X																
Little Tern																		X						X		X
Grey-backed Tern	X	X		X	X	X	X			X		X		X	X	X	X	X				X	?	X		X
Sooty Tern	X	X					X			X				X	X			X			X		X			X
Brown Noddy	X	X		X	X	X	X			X		X		X	X	X	X	X			X	X	X	X		X
Black Noddy	X	X				X				X		X		X	X			X				?	X	X		X
Blue Noddy	X	X				X						X														
White Tern	X	X				X	X			X		X		X	X			X								

Table 7.3. Distribution of seabirds in the Pacific, Main Hawaiian Islands (MHI) and the NWHI. Source: USFWS, 2005.

COMMON NAME	SCIENTIFIC NAME	NWHI	MHI	USPI
Procellariiformes (Albatrosses, Petrels and Shearwaters)				
Black-footed Albatross	*Phoebastria nigripes*	B	B	B
Laysan's Albatross	*Phoebastria immutabilis*	B	B	B
Short-tailed albatross	*Phoebastria albatrus*	b		
Hawaiian Petre	*Pterodroma sandwichensis*		B	
Herald Petrel	*Pterodroma arminjoniana*			B
Tahiti Petrel	*Pterodroma rostrata*			B
Bonin Petrel	*Pterodroma hypoleuca*	B	Ex	B
Phoenix Petrel	*Pterodroma alba*			Ex
Bulwer's Petrel	*Bulweria bulwerii*	B	B	B
Wedge-tailed Shearwater	*Puffinus pacificus*	B	B	B
Christmas Shearwater	*Puffinus nativitatis*	B	B	B
Newell's Shearwater	*Puffinus auricularis newelli*		B[1]	
Audobon's Shearwater	*Puffinus lherminieri*			B
Band-rumped Storm-Petrel	*Oceanodroma castro*		B	B
Black Storm-Petrel	*Oceanodroma melania*		B	
Tristram's Storm-Petrel	*Oceanodroma tristrami*	B		B
Polynesian Storm-Petrel	*Nesofregetta fuliginosa*			B
Pelecaniformes (Tropicbirds, Boobies and Frigatebirds)				
White-tailed Tropicbird	*Phaethon lepturus dorothea*	B	B	B
Red-tailed Tropicbird	*Phaethon rubricauda melanorhynchos*	B	B	B
Masked Booby	*Sula dactylatra personata*	B	B?	B
Brown Booby	*Sula leucogaster plotus*	B	B	B
Red-footed Booby	*Sula sula rubripes*	B	B	B
Great Frigatebird	*Fregata minor palmerstoni*	B	b	B
Lesser Frigatebird	*Fregata ariel ariel*			B
Charadriiformes (Terns and Noddies)				
Little Tern	*Sterna albifrons sinensis*	B		B
Gray-backed Tern	*Sterna lunata*	B	B?	B
Bridled Tern	*Sterna anaethetus*			B?
Sooty Tern	*Sterna fuscata oahuensis*	B	B?	B
Brown Noddy	*Anous stolidus pileatus*	B	B	B
Black Noddy	*Anous minutus marcusi*	B	B	B
Blue Noddy	*Procelsterna cerulea saxatilis*	B	B?	B
White Tern	*Gygis alba alba*	B	B	B

Note: [1]Endemic
Abbreviations: B = breeding; b = unsuccessful breeding attempts; B? = breeding suspected; Ex = extirpated breeders

PROCELLARIIFORMES (ALBATROSSES, PETRELS AND SHEARWATERS)

Laysan Albatross (*Phoebastria immutabilis*)

Laysan Albatrosses are a relatively small albatross species, with a body length of 79-81 cm, a wingspan of 195-203 cm, and a mean body mass of 2.4 kg (Whittow, 1993; Suryan et al. 2008; Figure 7.3). Like Black-footed Albatrosses (*P. nigripes*) and other Procellariiformes, males are slightly larger than females but feather plumage is identical for both sexes. Laysan Albatrosses have a white head, neck, and underparts, and sooty brown upper wings and trailing edges of under wings, and back. The legs, feet, and bill are pink but the bill also has a greenish tip (Whittow, 1993).

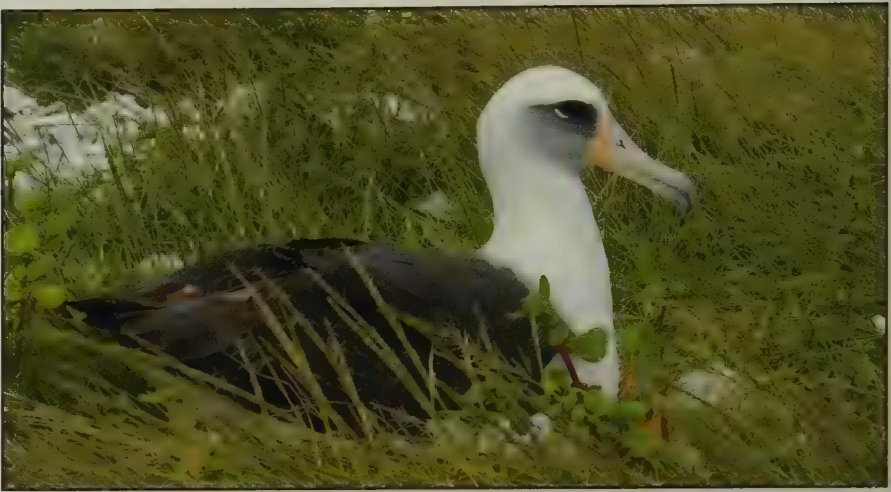


Figure 7.3. Laysan Albatross, Tern Island and French Frigate Shoals. Photo: C. Gregory.

When breeding, Laysan Albatrosses nest on all of the islands and atolls of the NWHI chain, and at discrete colonies on Kauai and Oahu, Torishima Island, Japan (Kurata, 1978), and off of the west coast of Baja, Mexico (USFWS, 2005). A pair was also documented to have successfully bred on Wake Island in 2001 (USFWS, 2005; Figure 7.4). In the NWHI, egg laying and incubation are generally synchronous, occurring from November to January. Chicks are reared from late January to mid-July and fledge in mid to late July (USFWS, 2005). Most birds breed every year but will occasionally skip a breeding event (Fisher, 1976).

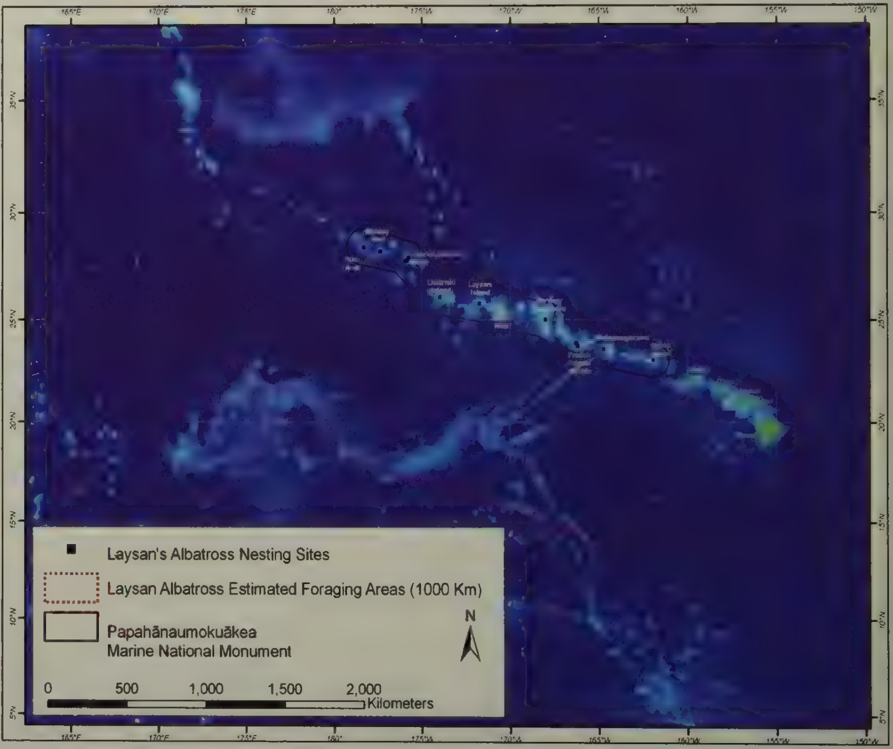

Laysan's Albatross Nesting Sites
Laysan Albatross Estimated Foraging Areas (1000 Km)
Papahānaumokuākea
Marine National Monument
N
0
500
1,000
1,500
2,000
Kilometers

Figure 7.4. Laysan Albatross nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

In the NWHI, predator control, including rat eradication, has reduced some of the threats to Laysan Albatrosses, but existing impacts to nesting habitat include the invasive wildflower golden crownbeard (*Verbesina encelioides*), other non-native plant species, obstacles to flying (USFWS, 2005), and lead toxicity in chicks at Midway from ingestion of lead paint chips from dilapidated buildings (Finkelstein et al., 2003). Threats at sea include the ingestion of marine debris (e.g., plastics), sea level rise and long-line bycatch (USFWS, 2005).

When at sea, tracking studies reveal that Laysan Albatrosses are found throughout the North Pacific (including the Bering Sea) but generally range between 30°N and 55°N (Harrison, 1987; Fernandez et al., 2001; Hyrenbach et al., 2002; Shaffer et al., 2005). During the incubation period, adults conduct foraging excursions lasting 10-30 days and may travel over 2,000 km from the nesting colony (Kappes et al., in review, Figures 7.4 and 7.5). Albatrosses studied across several consecutive years (2002-2006) show that habitat use changes across years (Figure 7.5) but the environmental cues that putatively influence foraging effort remain the same across years studied. That is, sea surface temperature (SST) and primary productivity levels appear to be the most important predictors of searching/foraging activity (Kappes et al., in review). During the chick-brooding period, adults are constrained by the need to provision their chick frequently so foraging excursions last only one to three days on average and range from the colony is typically less than 400 km (Kappes et al., unpublished data). When chicks are large enough to defend themselves and are thermally independent, both parents are able to forage simultaneously. During this period (i.e., chick-rearing), adults conduct both long and short duration foraging trips with some trips extending northward to the Aleutian Islands (Fernandez et al., 2001; Hyrenbach et al., 2002). When breeding is complete, adult Laysan Albatrosses depart the breeding colonies for cool waters of the Central and Western North Pacific including the Bering Sea and Aleutian Islands (Shaffer et al., submitted; Figure 7.5). Here, birds remain for most of the summer months while undergoing molt and recovering from breeding. Albatrosses return to the colonies in mid- to late-November to breed again. It is important to note the this species has only been tracked from a few of their breeding colonies, thus at sea distribution is not fully characterized. Laysan Albatrosses are surface feeders, with a diet consisting of squid, crustaceans, fish and flying fish eggs. At least 50% of the diet is composed of squid (USFWS, 2005).

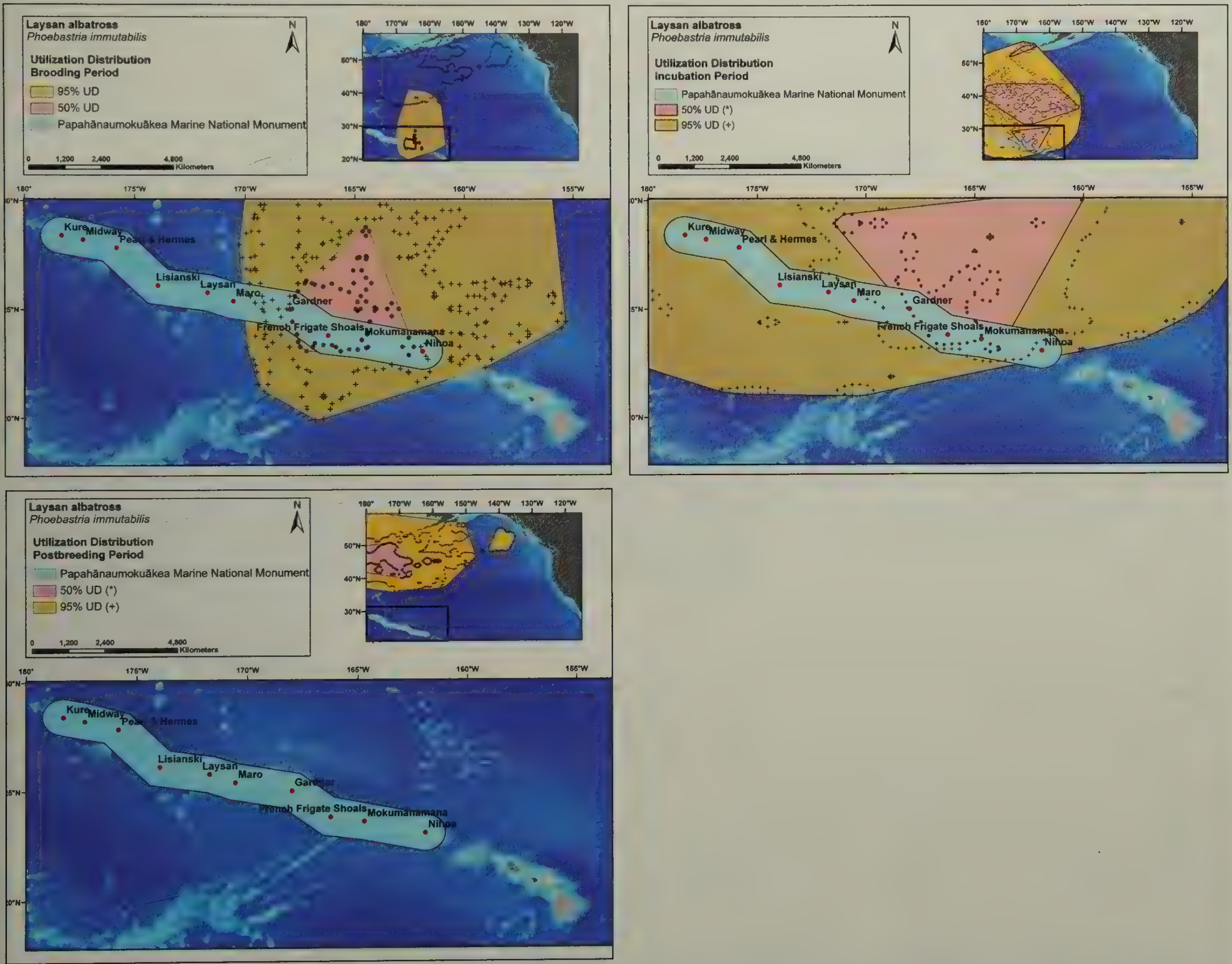


Figure 7.5. Laysan Albatross utilization distribution during brooding, incubation and postbreeding. Source: Shaffer et al., in review; maps: R. Clark.

Black-footed Albatross (*Phoebastria nigripes*)

Black-footed Albatrosses are slightly larger than Laysan Albatrosses, with a body length of 64-74 cm, a wingspan of 193-216 cm, and a mean body mass of 2.8 kg (Awkerman et al., 2008; Suryan et al., 2008; Figure 7.6). Like Laysan Albatrosses, males are slightly larger than females but plumage is identical between the sexes. Black-footed Albatrosses are dusky-brown with white fringes around the base of the bill, under the eye, under the tail, and over the base of the tail (Harrison, 1987).

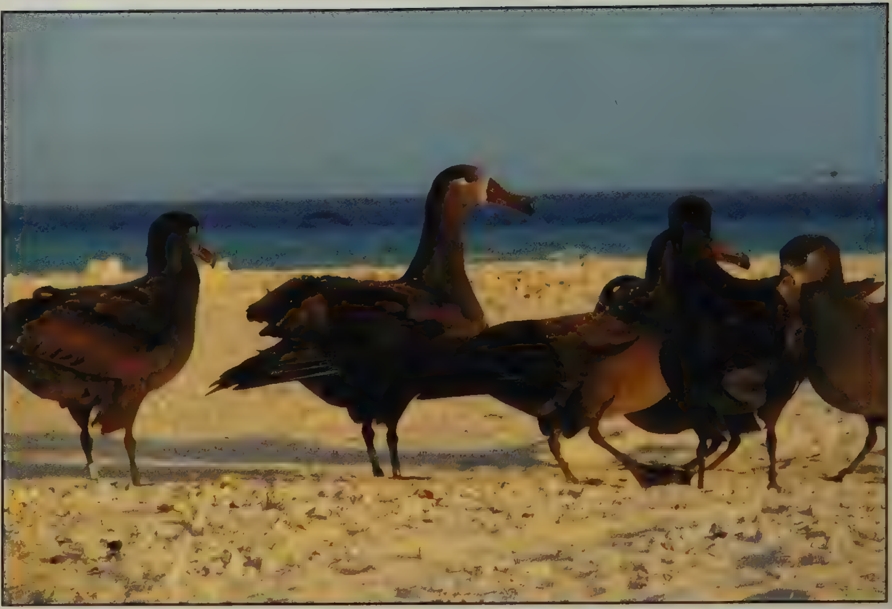
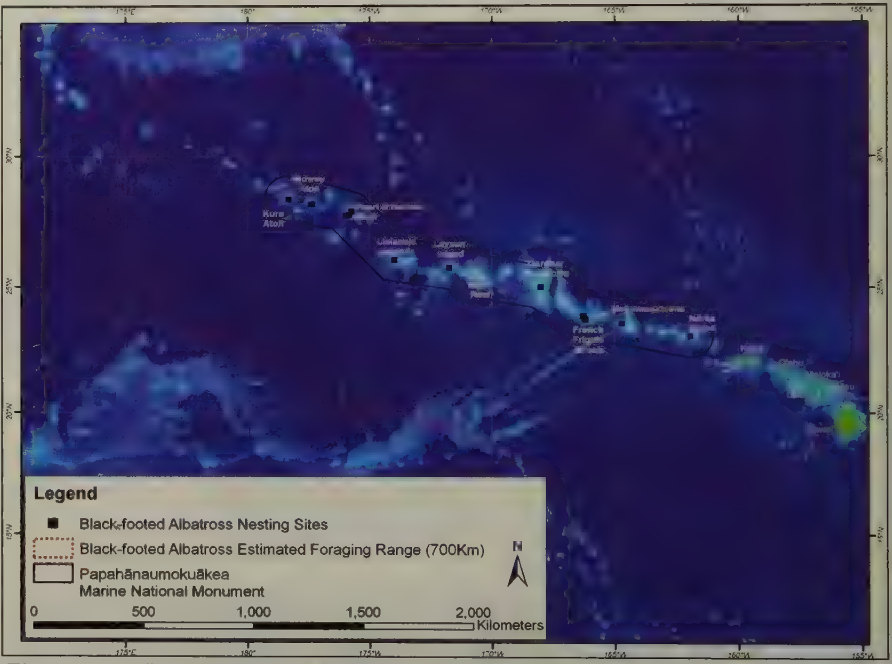


Figure 7.6. Black-footed Albatross, Tern Island and French Frigate Shoals. Photo: C. Gregory.

Ninety eight percent of the breeding population occurs within the Monument. The species nests on all of the islands and atolls in the NWHI, with the majority of pairs nesting at Midway Atoll and on Laysan Island (USFWS, 2005; Figure 7.7). A few thousand (Awkerman et al., 2008) Black-footed Albatrosses also breed on discrete colonies in Japanese Islands, and several pairs have been observed prospecting at Guadalupe Island, Baja, Mexico. Within breeding colonies, Black-footed Albatrosses nest synchronously, with all females laying eggs within a few-week period. Throughout the Hawaiian archipelago, egg-laying and incubation generally occurs from October through December, and chicks are reared from January to June, with fledging occurring in mid-June (Awkerman et al., 2008). Historical breeding areas include the Hawaiian archipelago and Marshall, Johnston, and Torishima Islands (Harrison, 1987).



Kure Atoll
French
Legend
■ Black-footed Albatross Nesting Sites
Black-footed Albatross Estimated Foraging Range (700Km)
Papahānaumokuākea
Marine National Monument
N
0
500
1,000
1,500
2,000
Kilometers

Figure 7.7. Black-footed Albatross nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Within the Monument, many threats have been reduced over the years, but existing threats include ingestion of plastics, long-line bycatch, and sea level rise (USFWS, 2005; Lewison and Crowder, 2003). The Monument provides protection for breeding and nesting habitat, but only a small portion of the foraging range remains protected because of the wide ranging foraging behavior.

When at sea, tracking studies reveal that Black-footed Albatrosses are found throughout the North Pacific (partially the Bering Sea) but generally they range between 25°N and 50°N (Harrison, 1987; Fernandez et al., 2001; Hyrenbach et al., 2002; Shaffer et al., 2005). During the incubation period, adults conduct foraging excursions lasting 10-20 days in duration and may travel over 1,500 km from the nesting colony (Kappes et al., in review; Figures 7.7 and 7.8). Adults tend to head north-northeast of the breeding islands to warmer waters along the southern edge of the North Pacific Current. Like Laysan Albatrosses, Black-footed Albatrosses studied across multiple consecutive years (2002-2006) use slightly different habitat across years (Figure 7.8) but the environmental cues that putatively influence foraging effort remain the same across years studied. That is, SST and primary productivity levels appear to the most important predictors of searching/foraging activity (Kappes et al., in review). During the chick-brooding period, adult Black-footed and Laysan Albatrosses experience the greatest overlap in their distribution because adults are constrained by the need to provision their chick frequently; thus foraging excursions last only one to three days on average and ranges are typically less than 300-400 km from the colony (Kappes et al., unpublished data). During the chick-rearing period, adults conduct both long and short duration foraging trips with some trips extending to the west coast of the U.S. and Canada (Fernandez et al., 2001; Hyrenbach et al., 2002). After breeding, adult Black-footed Albatrosses leave the breeding colonies for rich productive waters of the California Current and Aleutian Islands (Hyrenbach et al., 2006; Fischer, 2008; Shaffer et al., submitted; Figure 7.8). Thus, the spatial overlap with Laysan Albatrosses during the non-breeding period can be relatively minor (<10%; Shaffer et al., submitted). Black-footed Albatrosses remain along the West Coast of the U.S. or Aleutian Islands for most of the summer months while undergoing molt and recovering from breeding. Albatrosses return to breeding colonies in mid- to late-October to breed again. It is important to note the this species has only been tracked from a few of their breeding colonies, thus at sea distribution is not fully characterized. The species is a surface feeder, with a diet including fish eggs, squid, crustaceans, fish, and zooplankton. Forty percent of the diet is composed of flying fish eggs (USFWS, 2005).

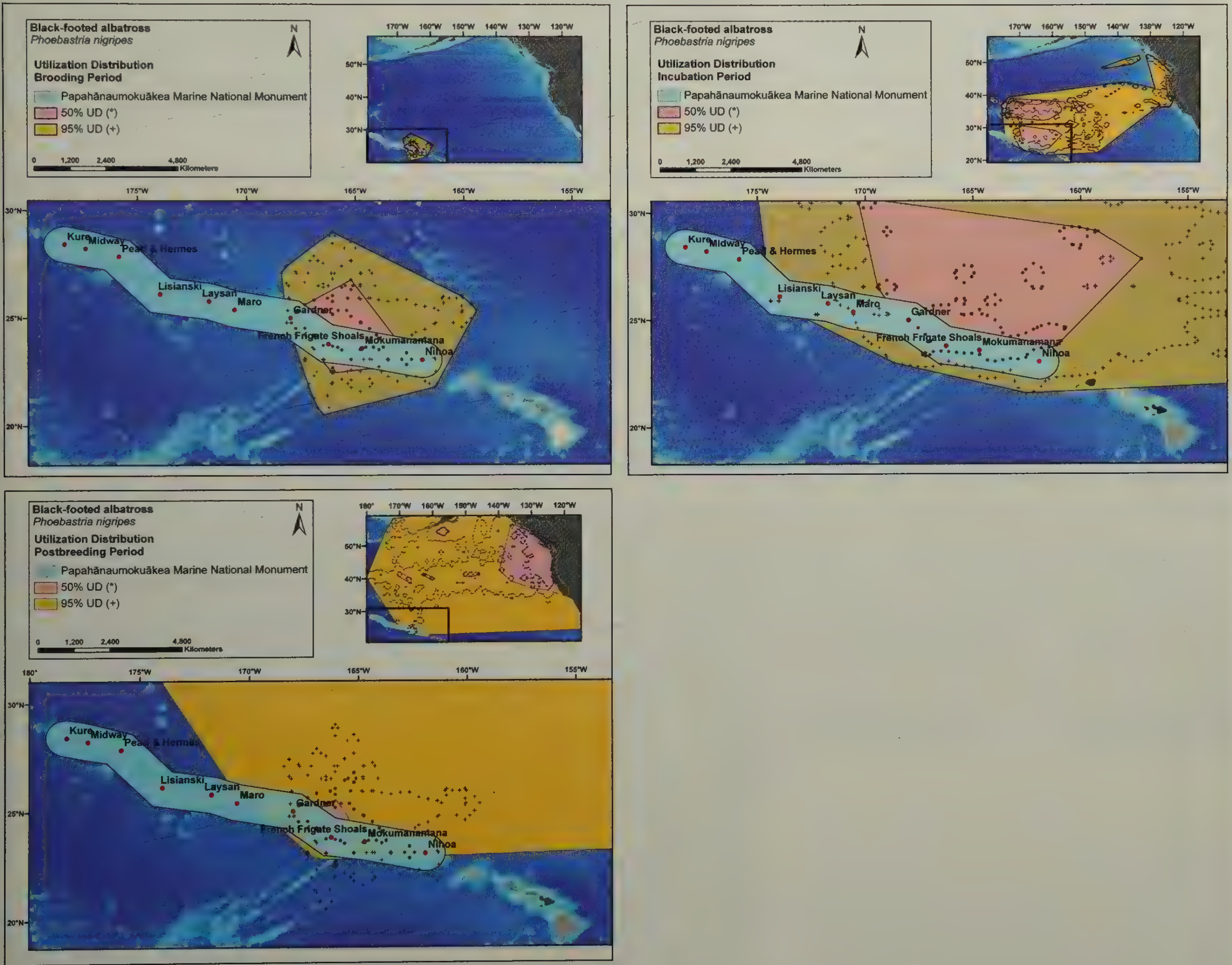


Figure 7.8. Black-footed Albatross utilization distribution during brooding, incubation and postbreeding. Source: Shaffer et al., in review; maps: R. Clark.

Short-tailed Albatross (*Phoebastria albatrus*)

Short-tailed Albatrosses are larger than Laysan and Black-footed Albatrosses, with a mean wingspan of 237 cm and mean body mass of 4.3 kg (Brooke, 2004; Suryan et al., 2008). Short-tailed Albatrosses are similar in appearance to Laysan Albatrosses, but are larger, with a heavier bright pink bill, and with a yellow wash on the white plumage of the head and neck (Harrison, 1990; Figure 7.9).

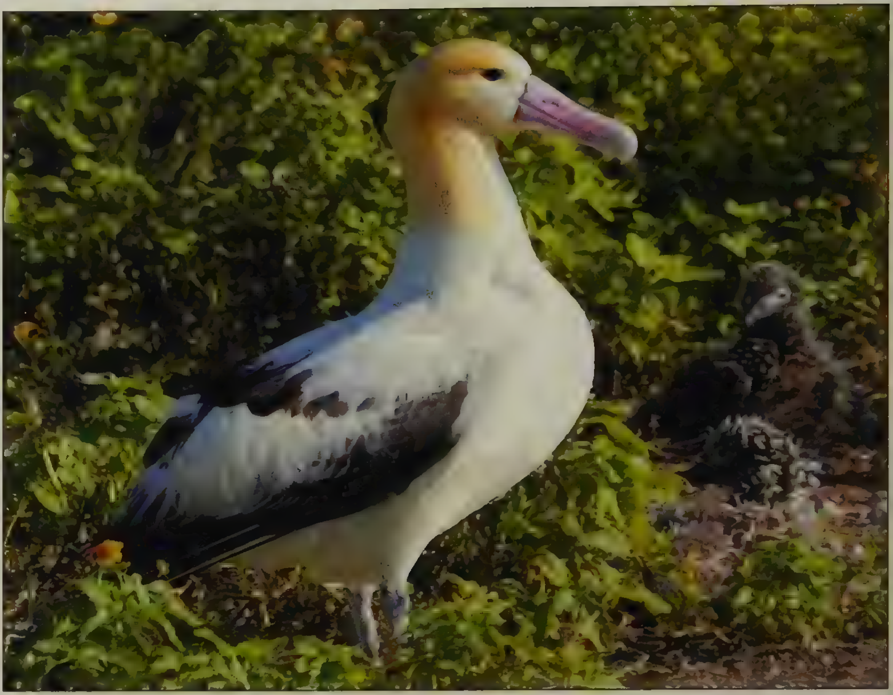


Figure 7.9. Short-tailed Albatross. Photo: J. Lloyd.

Short-tailed Albatrosses historically ranged throughout the North Pacific, but current breeding sites include only Torishima and Minami-kojima, Japan (USFWS, 2005). Short-tailed Albatrosses periodically do attempt to breed at Midway Atoll, but there are no documented accounts of successful nesting (USFWS, 2005). Eggs are laid from October to November and fledging occurs in June.

The Short-tailed Albatross is listed as Endangered under the Endangered Species Act (ESA) throughout its range. Within the Monument, threats are minimal relative to other potential colony sites, and management actions are taking place to encourage nesting at Midway Atoll. Tracking studies show that these albatrosses generally remain in the Western Pacific when breeding, and then move further north into the Bering Sea and along the Aleutian Islands (Suryan et al., 2006). Based on the large body size of Short-tailed Albatrosses compared to Laysan and Black-footed albatrosses, Short-tailed Albatrosses would appear to have a more restricted range that occurs within regions of stronger winds and larger wave heights (Suryan et al., 2008).

Bonin Petrel (*Pterodroma hypoleuca*)

Bonin Petrels are 30 cm long with a wingspan of 63-71 cm and a mean body mass of 204 g. Plumage on the upper parts is blue- to silver-gray, with a sooty head and neck, and white forehead, chin and throat. Upper wings are gray with black primaries, and the underwing is white with black margins (Seto and O'Daniel, 1999; Figure 7.10).

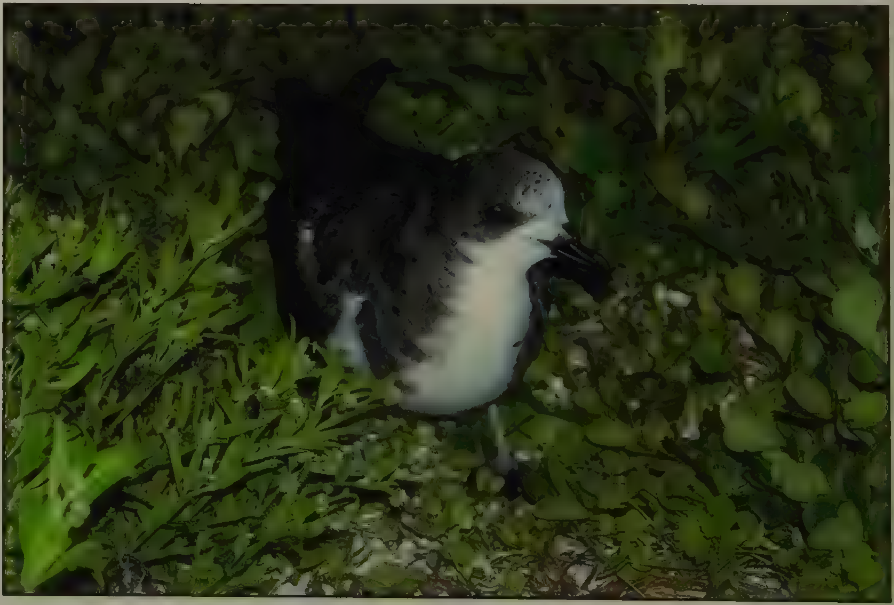


Figure 7.10. Bonin Petrel. Photo: C. Gregory.

Bonin Petrels are found throughout the western north Pacific and breed in the NWHI and on Volcano and Bonin Islands in Japan. There are no breeding colonies of Bonin Petrels in the Main Hawaiian Islands (MHI; Harrison, 1987).

In the NWHI, Bonin Petrels nest at French Frigate Shoals, Laysan Island, Lisianski Island, Pearl and Hermes Atoll, Midway Atoll and Kure Atoll. Gardner Pinnacles may also provide nesting habitat. Lisianski Island, Laysan Island and Midway Atoll support the largest colonies in the archipelago (Figure 7.11). In the NWHI, eggs are laid from December to March and chicks are reared from February to May.

Bonin Petrels are nocturnal surface feeders, with a diet consisting mainly of fish (USFWS, 2005).

Habitat loss from erosion and invasive plant species are some of the main threats to the populations in the NWHI. Historically, introduced Polynesian rats posed a serious threat to Bonin Petrel populations, but rats were extirpated in the NWHI by the year 2000. The U.S. Fish and Wildlife Service (USFWS) has also modified light sources at Midway Atoll and French Frigate Shoals to reduce impacts to nocturnal seabird species, including the Bonin Petrel.

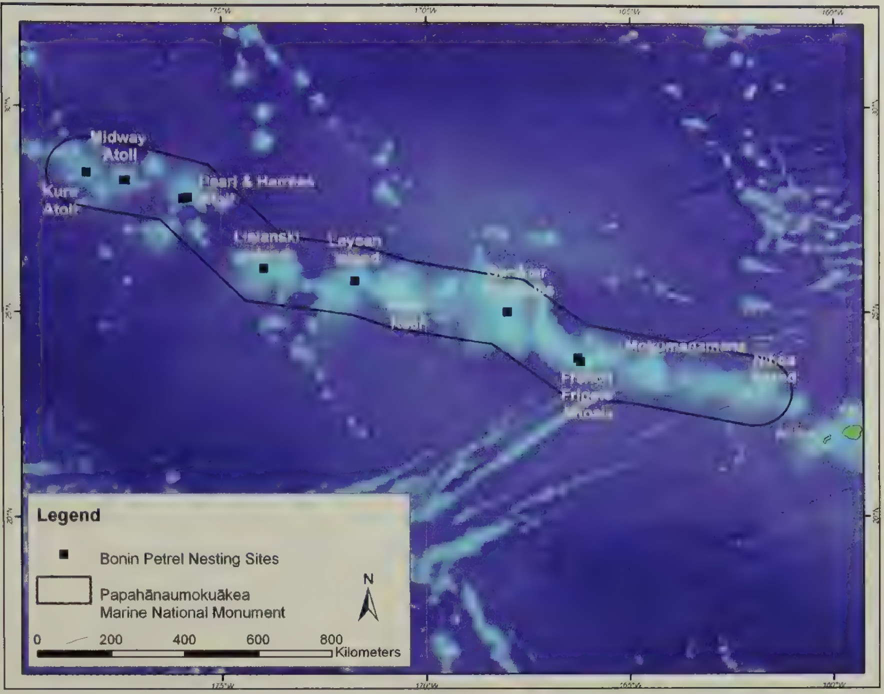


Figure 7.11. Bonin Petrel nesting sites in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Bulwer's Petrel (*Bulweria bulwerii*)

The Bulwer's Petrel is 26 cm long with a 67 cm wingspan (Harrision, 1987). Plumage is sooty brown, with a lighter brown face and chin (Megysi and O'Daniel, 1997; Figure 7.12).

The Bulwer's Petrel is a wide-ranging species occurring in the tropical and subtropical waters of the Pacific, Atlantic and Indian Oceans (Harrision, 1987). In the Pacific, Bulwer's Petrels breed in the Phoenix, Marquesas, Bonin, Volcano and Hawaiian Islands, including the NWHI and MHI (USFWS, 2005). From the little that is known about the species' at-sea distribution, it appears that the Hawaiian populations travel to the central and eastern Pacific during the non-breeding period (USFWS, 2005).

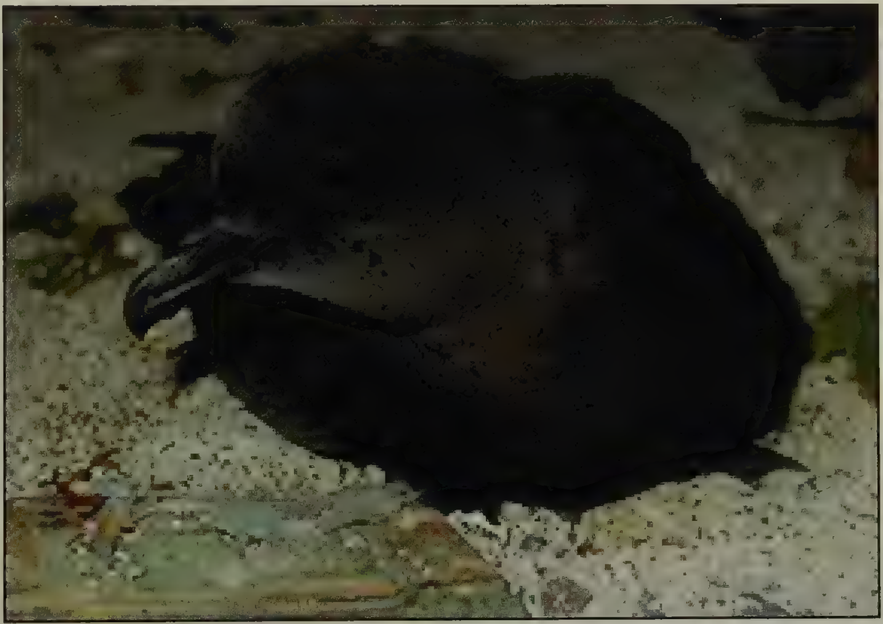


Figure 7.12. Bulwer's Petrel. Photo: USFWS.

In the NWHI, Bulwer's Petrels have been found to breed at Nihoa Island, Mokumanamana, French Frigate Shoals, Laysan Island, Lisianski Island, Pearl and Herrmes Atoll and Midway Atoll (Figure 7.13). The largest breeding colony occurs on Nihoa Island. Bulwer's Petrels lay eggs in the NWHI between May and July. Chicks are present from July to October, and fledging occurs by early October.

Bulwer's Petrels are nocturnal surface feeders, with a diet composed of fish, squid, crustaceans and sea-striders. Most of the prey species are bioluminescent and are found in upwelling areas (USFWS, 2005).

As seen with many of the seabirds in the NWHI, Bulwer's Petrels suffered losses to Polynesian rat and ant introductions.

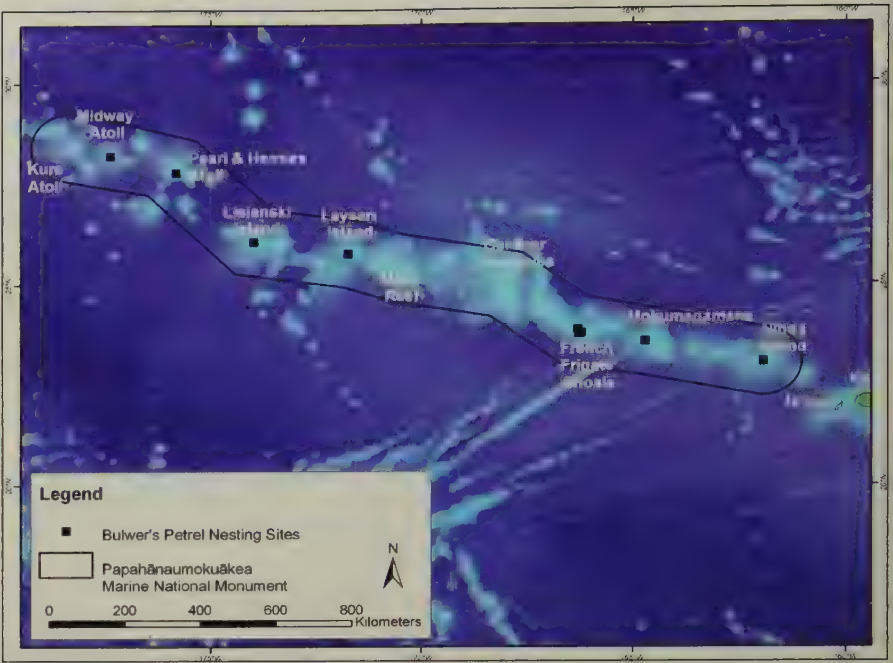


Figure 7.13. Bulwer's Petrel nesting sites in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Wedge-tailed Shearwater (*Puffinus pacificus*)

The Wedge-tailed Shearwater is 43 cm long, with a wingspan of 101 cm (Harrison, 1987; Figure 7.14), and a mean body mass of 390 g (Whittow, 1997). Light-morph shearwaters are grayish brown above, with white underparts, while dark-morph individuals are sooty brown above and below (Whittow, 1997).

Wedge-tailed Shearwaters occur throughout the tropic and subtropical Pacific and Indian Oceans, including the NWHI (Harrison, 1987). The Hawaiian populations most likely migrate to the Equatorial Countercurrent and east during the non-breeding period (USFWS, 2005). This species aggregates into large multi-species feeding flocks, often associated with subsurface predators (e.g., tuna and dolphin).

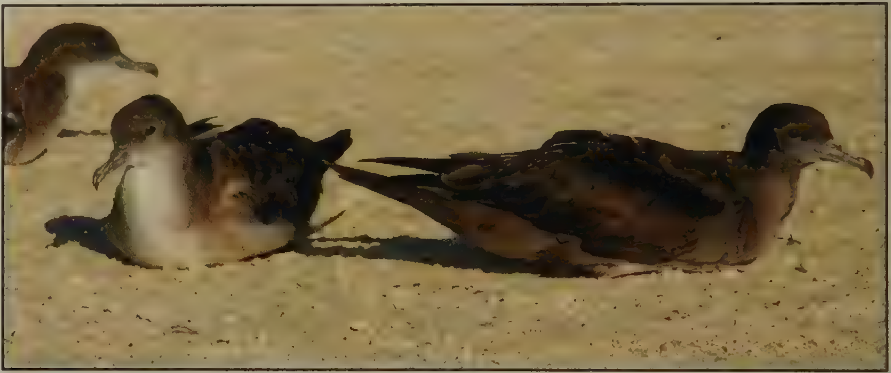


Figure 7.14. Wedge-tailed Shearwater light and dark morphs, Tern Island, French Frigate Shoals. Photo: USFWS.

Wedge-tailed Shearwaters nest on all of the islands and atolls in the NWHI (Figure 7.15). The largest colonies within the archipelago are at Nihoa Island, Laysan Island and Lisianski Island. In the NWHI, eggs are laid from June to August and chicks are present from August to December, with the majority of fledging occurring in November.

Wedge-tailed Shearwaters use contact dipping for feeding, and their diet in the Hawaiian Archipelago consists mainly of larval goatfish, flying fish, squirrelfish and squid (USFWS, 2005).

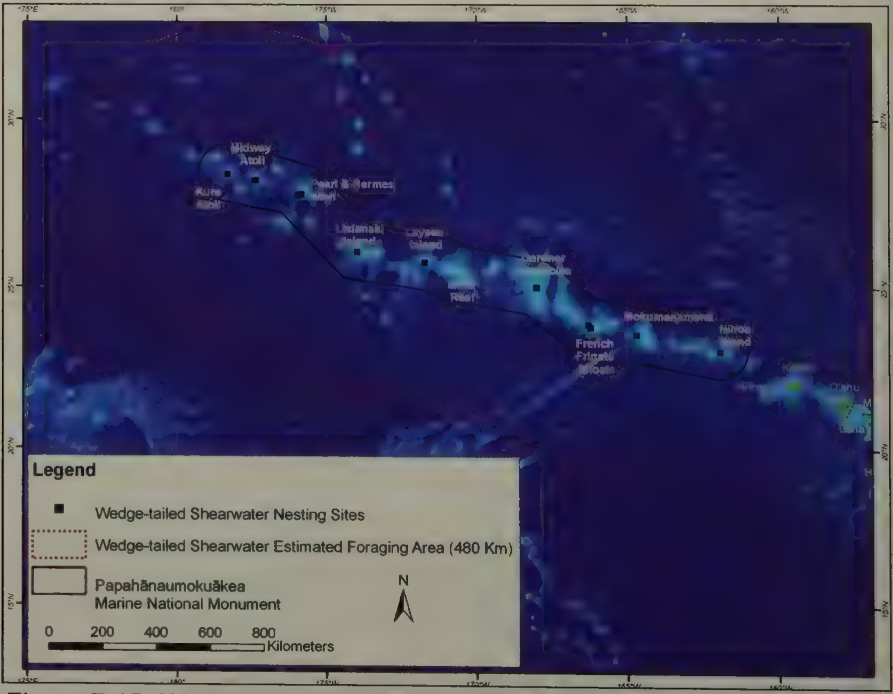


Figure 7.15. Wedge-tailed Shearwater nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller. .

Christmas Shearwater (*Puffinus nativitatis*)

Christmas Shearwaters are 36 cm long with a 76 cm wingspan (Harrison, 1987), and a mean body mass of 354 g (Seto, 2001). Plumage is dark brown throughout, with underparts slightly paler than upperparts (Seto, 2001; Figure 7.16).

Christmas Shearwaters occur in the tropical and subtropical Pacific (Harrison, 1987). The species nests on all of the islands and atolls in the NWHI, with the largest breeding colonies occurring on Laysan Island and Lisianski Island (USFWS, 2005; Figure 7.17). Females lay eggs from April through July, and chicks are reared from June to October.

Christmas Shearwaters use pursuit and plunge feeding behavior, with a diet composed of fish (goatfish, flying fish and scad) and squid (USFWS, 2005).

Nesting habitat degradation due to the spread of non-native invasive plant species is the most significant threat to the species in the NWHI.

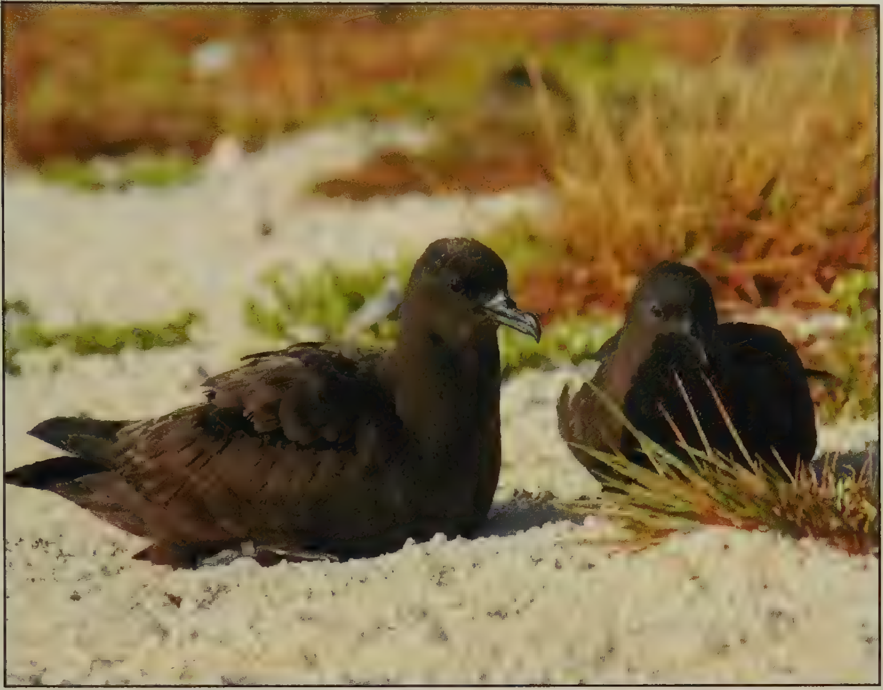


Figure 7.16. Christmas Shearwaters, Tern Island and French Frigate Shoals. Photo: D. Wright.

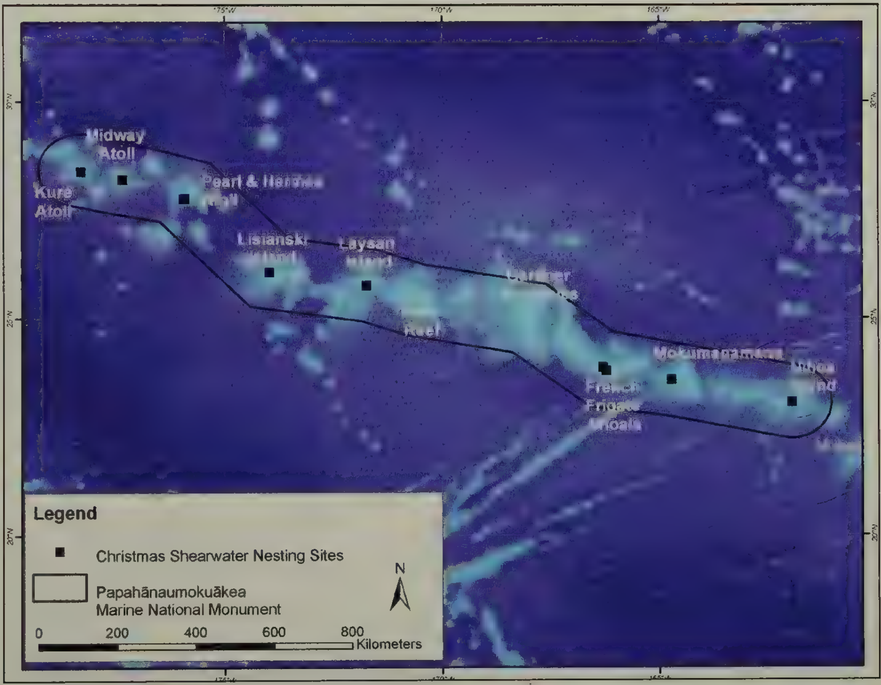


Figure 7.17. Christmas Shearwaters nesting sites in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Tristram's Storm-petrel (*Oceanodroma tristrami*)

The Tristram's Storm-petrel is the smallest Procellariiformes species in the NWHI. It averages 24 cm in length, with a 56 cm wingspan and a mean body mass of 77-97 g. The species is brownish gray throughout, with a buffy brown wing bar across the upper wing (Slotterback, 2002; Figure 7.18).

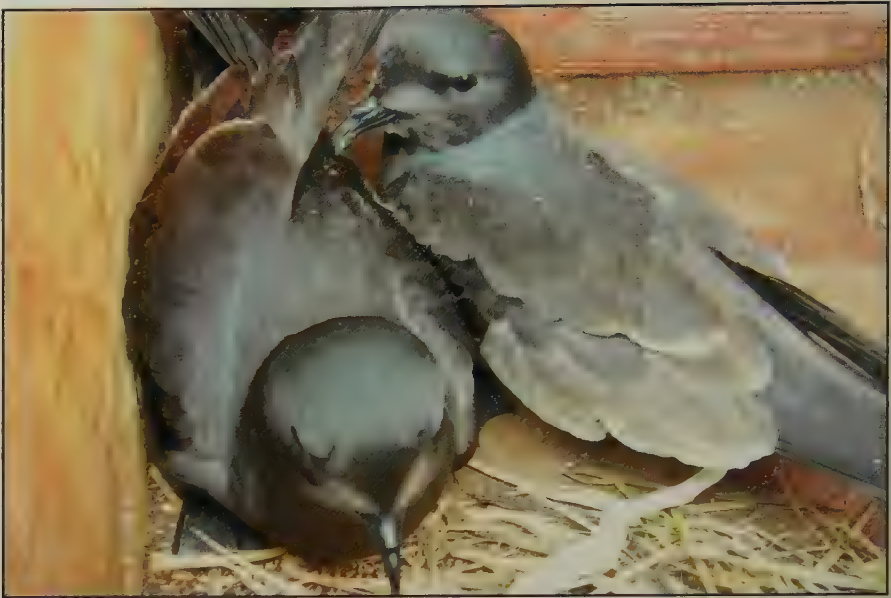


Figure 7.18. Tristram's Storm-petrel, Tern Island and French Frigate Shoals. Photo: C. Gregory.

The Tristram's Storm-petrel range includes the subtropical central and western Pacific and waters off of Japan. Breeding colonies occur in the NWHI, but there is no evidence of colonies in the MHI (USFWS, 2005).

The species is found on Nihoa Island, Mokumanamana, French Frigate Shoals, Laysan Island, Lisianski Island, and Pearl and Hermes Atoll. The largest colonies are at Nihoa Island, Laysan Island, and Pearl and Hermes Atoll (Figure 7.19). In the NWHI, eggs are laid from December to February, and chicks are present from February to May. Most birds have dispersed by June.

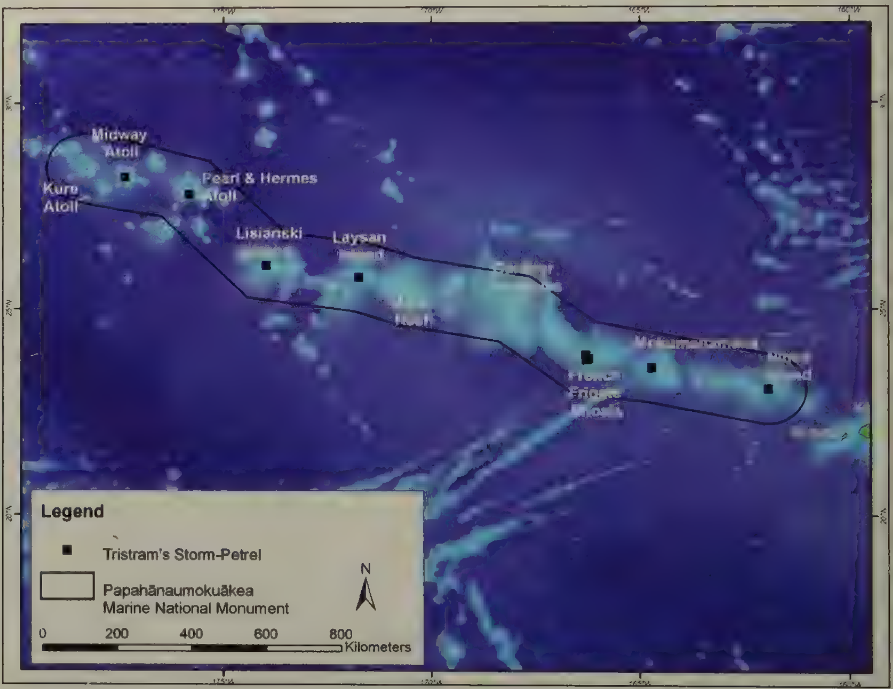


Figure 7.19. Tristram's Storm-petrel nesting sites in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

The feeding behavior of Tristram's Storm-petrels consists of pattering and snatching prey from the surface. Generally, the diet in the NWHI consists of small fish and squid and sometimes planktonic halobates (insects) and crustaceans (USFWS, 2005).

Breeding colonies were extirpated from Midway Atoll and Kure Atoll, most likely by the introduction of rats. Recolonization is possible due to the eradication of rats from these locations by the year 2000. Nesting habitat degradation from invasive plant species continues to be a threat at Pearl and Hermes Atoll.

PELECANIFORMES (BOOBIES, FRIGATEBIRDS AND TROPICBIRDS)

Red-footed Booby (*Sula sula rubripes*)

The Red-footed Booby is the smallest of the booby species worldwide, with a length of 69-79 cm and body mass of 850-1,100 g (Schreiber et al.,1996; Figure 7.20). Females are slightly larger than males. Adults in the NWHI are white, often with a yellowish wash on the head and neck, with black primaries, secondaries and coverts. A tan morph also occurs in the NWHI, but is present in much lower numbers and is seen only rarely (A. Anders, pers. comm.). Bills of females are blue with a pink base, and those of males lighter blue with a lime green and pink base. Legs and feet are orange-red to red (Schreiber et al., 1996).

Red-footed Boobies are a pantropical species, with the largest breeding colonies occurring in Palmyra and the Hawaiian Islands. Red-footed Boobies nest on all of the islands and atolls in the NWHI, as well as on Kauai, Oahu and offshore islets in the MHI (Figure 7.21). The species lays eggs from March to August and chicks occur from May to December.

The species forages farther than other boobies, ranging up to 276 km from the nesting colony (USFWS unpublished data; Figure 7.21). During the non-breeding period, the birds have been observed to travel several hundred kilometers from land (USFWS, 2005). The Red-footed Booby is a plunge diver, with primary prey species including flying fish and squid. This species often forages in large, multi-species flocks associated with subsurface predator.

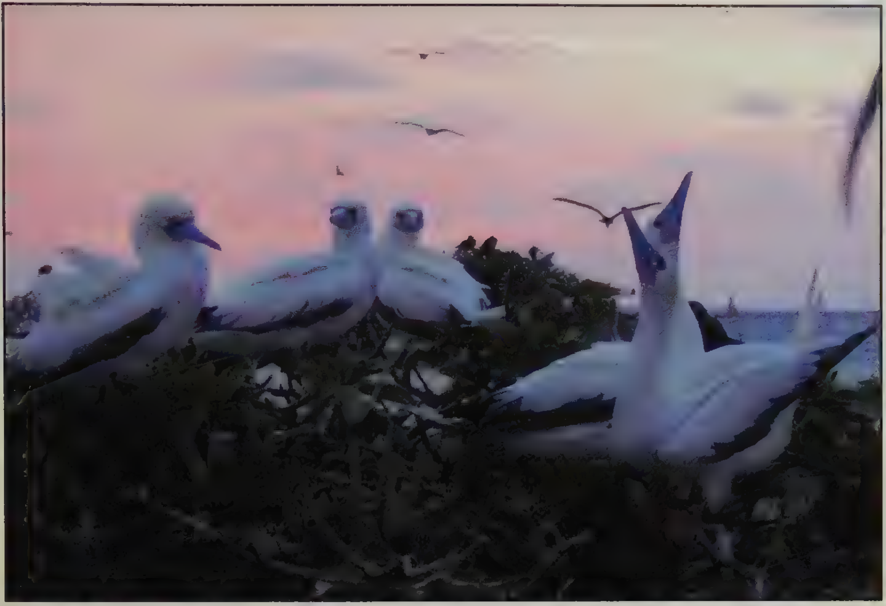


Figure 7.20. Red-footed Boobies, Tern Island, French Frigate Shoals. Photo: USFWS.

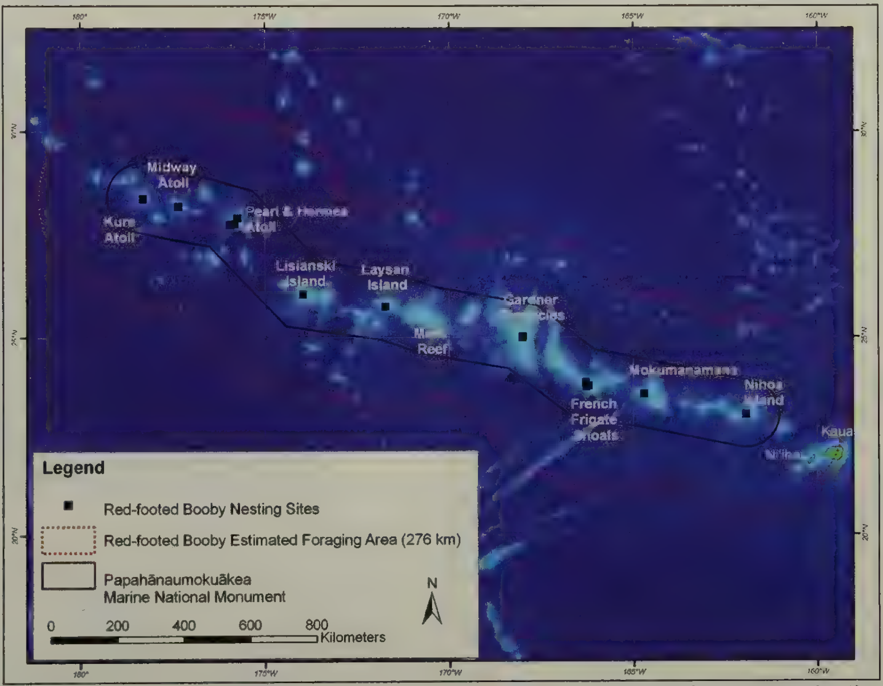


Figure 7.21. Red-footed boobies nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Habitat destruction is the main threat to populations in the NWHI (USFWS, 2005).

Masked Booby (*Sula dactylatra personata*)

Masked Boobies are the largest of the booby species, with a body length of 74-86 cm, and body mass of 1.2-2.4 kg. As with many other Pelecaniformes species, females are slightly larger than males. Adults are white with black-brown primaries, secondaries and tail, and purplish orange feet (Anderson, 1993; Figure 7.22).

Masked Boobies are a pantropical species, with the largest breeding colonies occurring on Howland, Baker and Jarvis. In the NWHI, the species occurs on all of islands and atolls (Figure 7.23). Eggs are present from January to July, and chicks occur from March to October.

During the breeding season, birds forage up to 160 km from the breeding colonies (USFWS unpublished data; Figure 7.23), and during the non-breeding period individuals may travel from 1,000 – 2,000 km from the breeding colonies (USFWS, 2005). Masked Boobies are plunge divers, with the majority of the diet consisting of fish, particularly flying fish and jacks. A very small portion of the diet is squid (USFWS, 2005).

The primary threats to the Masked booby populations in the NWHI are habitat destruction and loss of nesting habitat due to invasive plants (USFWS, 2005).

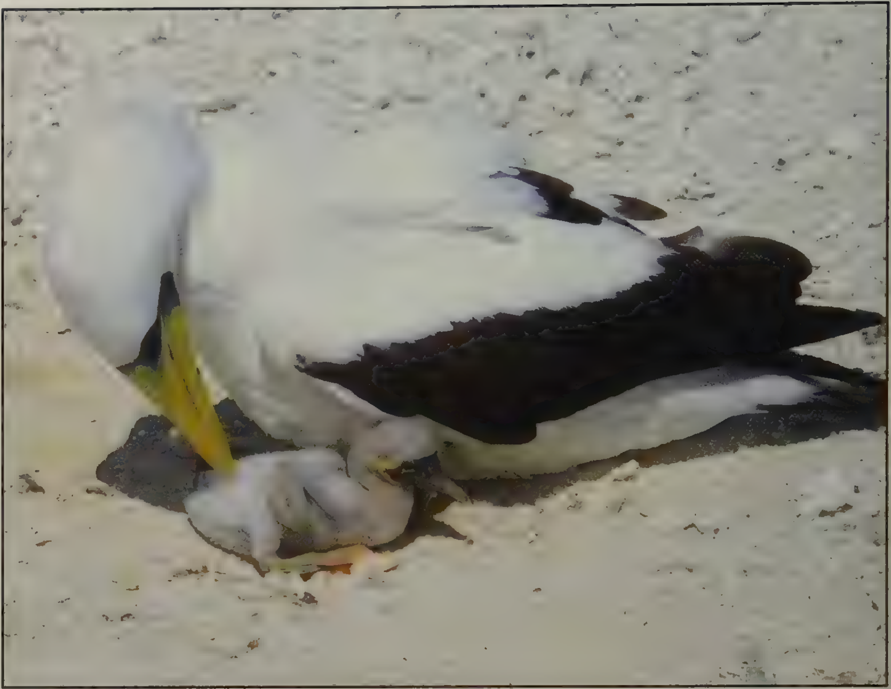


Figure 7.22. Masked Booby with chick, Tern Island, French Frigate Shoals. Photo: NOAA.

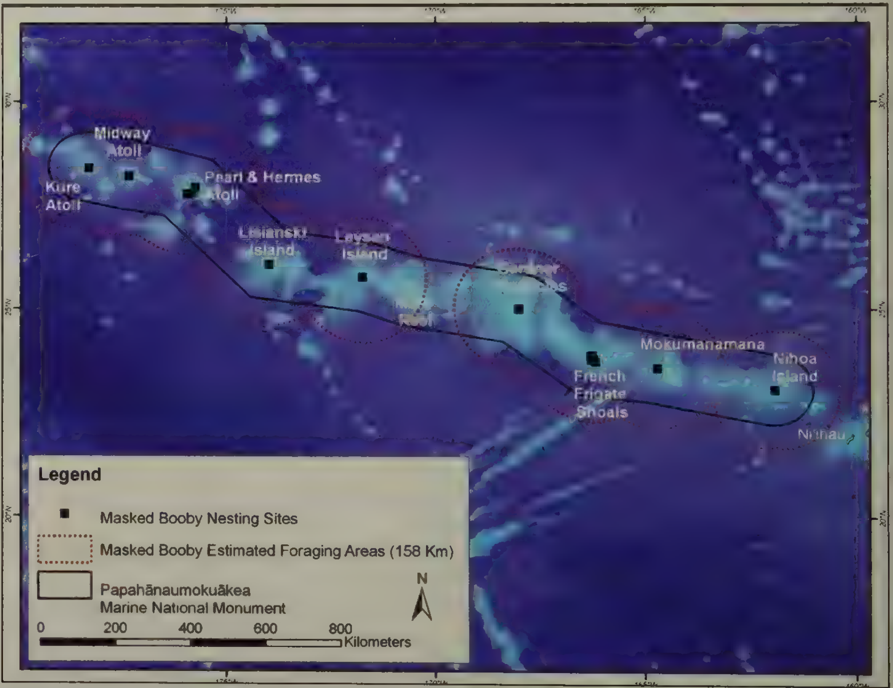


Figure 7.23. Masked Booby nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Brown Booby (*Sula leucogaster plotus*)

The Brown Booby is a medium-sized booby, with a body length of 64-85 cm, a wingspan of 132-155 cm, and body mass of 950-1,800 g (Schreiber and Norton, 2002). Females are markedly larger than males. Adults are deep brown on the back, head, neck and throat, with bright white underparts. In the NWHI, adults have a pale yellow bill with a light blue base, and bluish yellow legs and feet (A. Anders, pers. comm.; Schreiber and Norton, 2002; Figure 7.24).

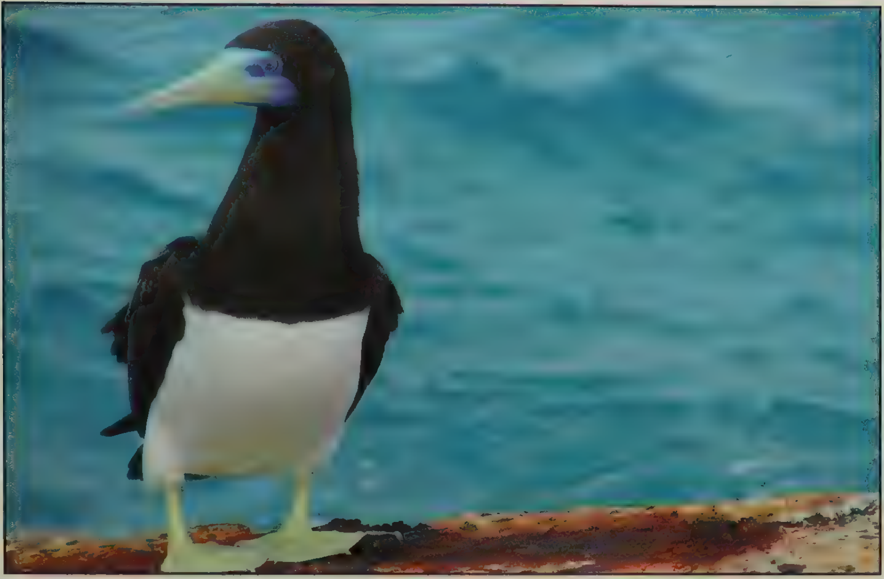


Figure 7.24. Brown Booby, Tern Island, French Frigate Shoals. Photo: J. Drury.

The Brown Booby distribution overlaps with those of the masked and Red-footed Booby species, which are pantropical (USFWS, 2005). The largest brown booby populations occur in the Hawaiian Islands, including the NWHI and MHI. The species nests within all of the islands and atolls of the NWHI. Brown Boobies lay eggs from February to August, and chicks are present from April to October (Figure 7.25).

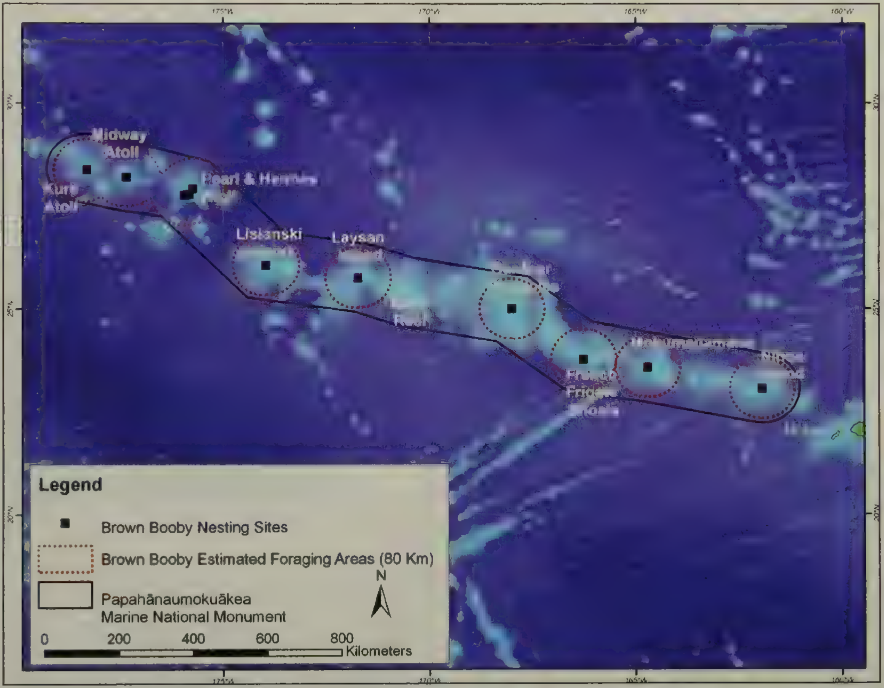

Midway Atoll
Kure Atoll
Pearl & Hermes
Lisianski
Laysan
French Frigate Shoals
Legend
Brown Booby Nesting Sites
Brown Booby Estimated Foraging Areas (80 Km)
Papahānaumokuākea Marine National Monument
N
0
200
400
600
800
Kilometers

Figure 7.25. Brown Booby nesting sites and foraging areas in the NWHI. Source: USFWS, 2005; map: K. Keller.

Foraging occurs near shore, at 8-70 km from land (USFWS, 2005; Figure 7.25). The species has been known to travel 2,000 km from breeding colonies during the nonbreeding season, but individuals generally remain within 80 km of land during the breeding period (USFWS, 2005). Brown Boobies are plunge divers, with primary prey species consisting of flying fish, squid, mackerel scad and juvenile goatfish (USFWS, 2005).

As with the other Booby species, the main threat to Brown Booby populations in the NWHI is habitat destruction (USFWS, 2005).

Great Frigatebird (*Fregata minor palmerstoni*)

Frigatebirds have the largest wing-area to body mass ratio of any avian species: Great Frigatebirds, with a length of 85-105 cm and wingspan of 205-230 cm, have a body mass of just 1-1.8 kg (Gauger Metz and Schreiber, 2002). Males are black or black-brown throughout, with a purple/blue/green sheen on the dorsal feathers of the neck and nape, and a red gular sac. The gular pouch is deflated and a pale pink-orange color during the non-breeding period, and becomes bright red and is inflated during display prior to the nesting period. Females are significantly larger than males, with a white throat, breast, and underparts and no (or a greatly reduced) gular sac (Gauger Metz and Schreiber, 2002; Figure 7.26).

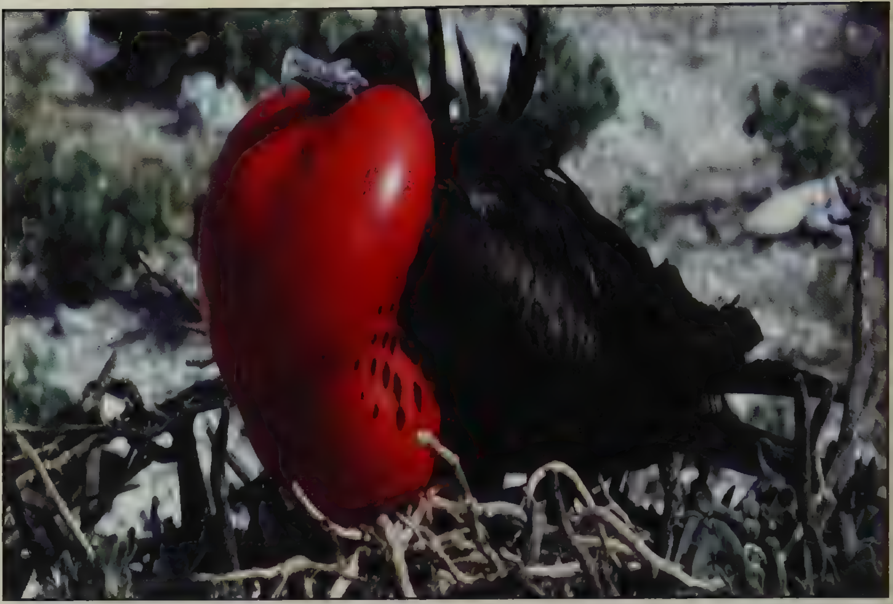
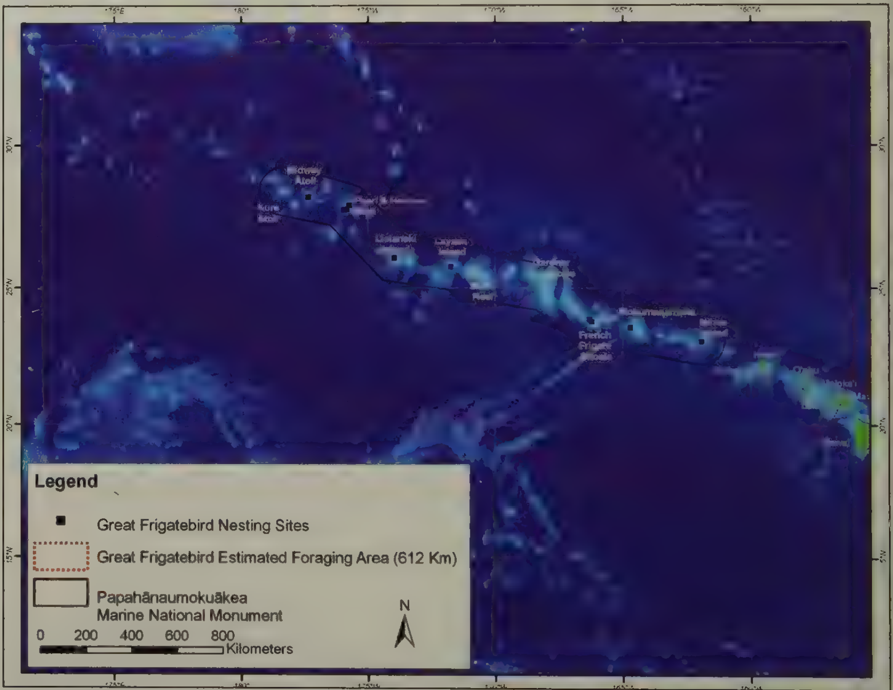


Figure 7.26. Male Great Frigatebird with inflated gular pouch, Tern Island, French Frigate Shoals. Photo: D. Dearborn.

The distribution of Great Frigatebirds is pantropical, with the largest breeding populations occurring on Nihoa Island and Laysan Island (USFWS, 2005). Great Frigatebirds nest on all of the islands and atolls within the NWHI except Gardner Pinnacles and Kure Atoll (Figure 7.27). In the NWHI, eggs are laid between March and July, and chicks are present from April to November.

Foraging ranges during the breeding season have been calculated to be up to 612 km (Weimerskirch et al., 2004), but frigatebirds travel up to 7,000 km during the non-breeding period (Dearborn et al., 2003; Figure 7.27). Great Frigatebirds cannot swim or land on water, and thus use surface dipping and aerial pursuit to capture prey. The main prey species are flying fish and squid (USFWS, 2005).



30°N
25°N
20°N
15°N
Midway Atoll
Kure Atoll
French Frigate Shoals
Legend
Great Frigatebird Nesting Sites
Great Frigatebird Estimated Foraging Area (612 Km)
Papahānaumokuākea Marine National Monument
N
0 200 400 600 800 Kilometers

Figure 7.27. Male Great Frigatebird nesting sites and foraging areas in the NWHI. Source: Weimerskirch et al., 2004; map: K. Keller.

The greatest threats to populations in the NWHI are habitat destruction and disturbance during nesting.

Lesser Frigatebird (*Fregata ariel ariel*)

Lesser Frigatebirds are significantly smaller than Great Frigatebirds, with a mean body length of 75 cm (Lindsey, 1986). Male plumage is similar to that of the Great Frigatebird, but with overall body plumage of lessers being darker black and with a brighter purple and green irredescence to the dorsal neck and nape feathers (Figure 7.28). Lesser males also have a bright white line on the underside of the wing, providing an obvious distinction in flight to the male Great Frigatebird (A. Anders, pers. comm.). Female lesser plumage is similar to that of female Great Frigatebirds, but with darker black feathers dorsally, and a full black hood giving a black, rather than white, throat (A. Anders, pers. comm.).

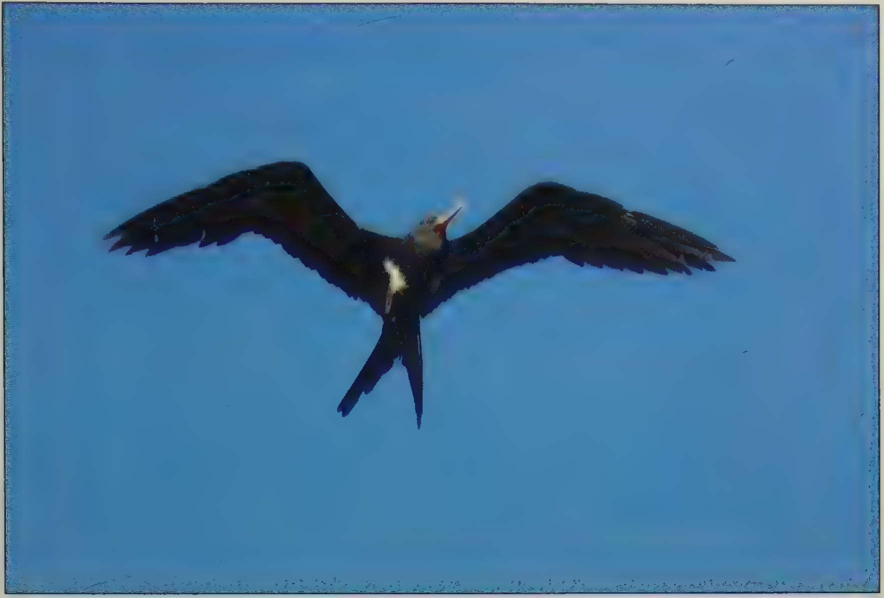


Figure 7.28. Lesser Frigatebird. Photo: USFWS.

The pantropical distribution of Lesser Frigatebirds lies within that of Great Frigatebirds, with the largest breeding colonies occurring on Baker and Howland Islands (USFWS, 2005). Individuals are observed roosting regularly but in low numbers in the NWHI; successful nesting of a Lesser Frigatebird male and Great Frigatebird female (with production of hybrid offspring) has been observed in multiple years at French Frigate Shoals (Figure 7.29), and one pair of Lesser Frigatebirds has been documented nesting on Tern Island, although the nest failed prior to hatching (Dearborn and Anders, 2000).

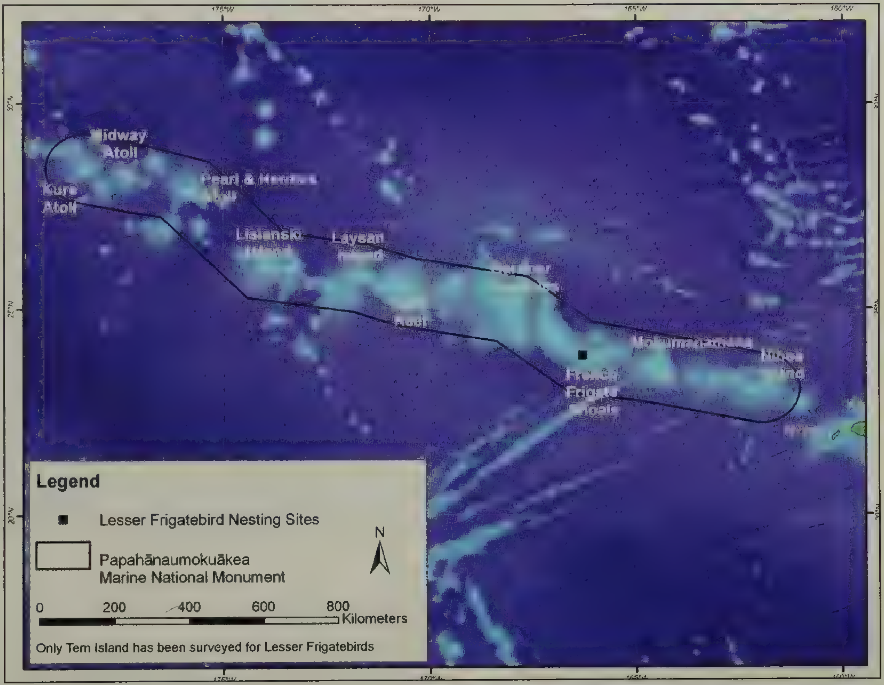


Figure 7.29. Lesser Frigatebird nesting sites in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

As with Great Frigatebirds, Lesser Frigatebirds use surface dipping to capture prey, and main food items include flying fish and squid. Lesser Frigatebirds travel thousands of kilometers from the breeding colonies during the non-breeding period, but are seen most often within 80 km of breeding and roosting islands (USFWS, 2005).

Red-tailed Tropicbird (*Phaethon rubricauda melanorhynchos*)

Red-tailed Tropicbirds are a relatively small, stout Pelecaniformes species, with a body length of 44-47 cm (80-102 cm including long central tail feathers), and body mass of 650-780 g (Schreiber and Schreiber, 1993). Plumage is white throughout, often with a pale pink wash. The bill is red-orange, and a black crescent eye ring extends to a short eye line (Figure 7.30). The tail is short and white, with two long red central rectrices.

The Red-tailed Tropicbird is distributed throughout the Indo-Pacific region between 35°N and 30°S. The largest concentration of breeding birds within the Pacific occurs in the NWHI at Midway Atoll and Laysan Island (Figure 7.31). Other smaller colonies are found on all of the other islands and atolls in the NWHI, in the MHI, and on other Pacific Islands such as Johnston Atoll, American Samoa, Wake and the Marianas (USFWS, 2005). Red-tailed tropicbirds lay eggs from March to August and chicks occur from April to November.

Foraging ranges have been calculated to be approximately 470 km from the breeding colonies, which extends beyond the boundaries of the Monument (USFWS unpublished data; Figure 7.31). Red-tailed Tropicbirds are solitary, plunge divers and feed mostly on flying fish. Other prey species include squid, mackerel scad, dolphinfish, truncated sunfish and balloonfish (USFWS, 2005). They are not associated with subsurface predator schools.

In the NWHI, rats on Midway Atoll and Kure Atoll, along with invasive plants, were the main threats to the species. Rats have been eradicated, and USFWS is currently conducting native plant restoration and other alien species removal projects to increase available nesting habitat.

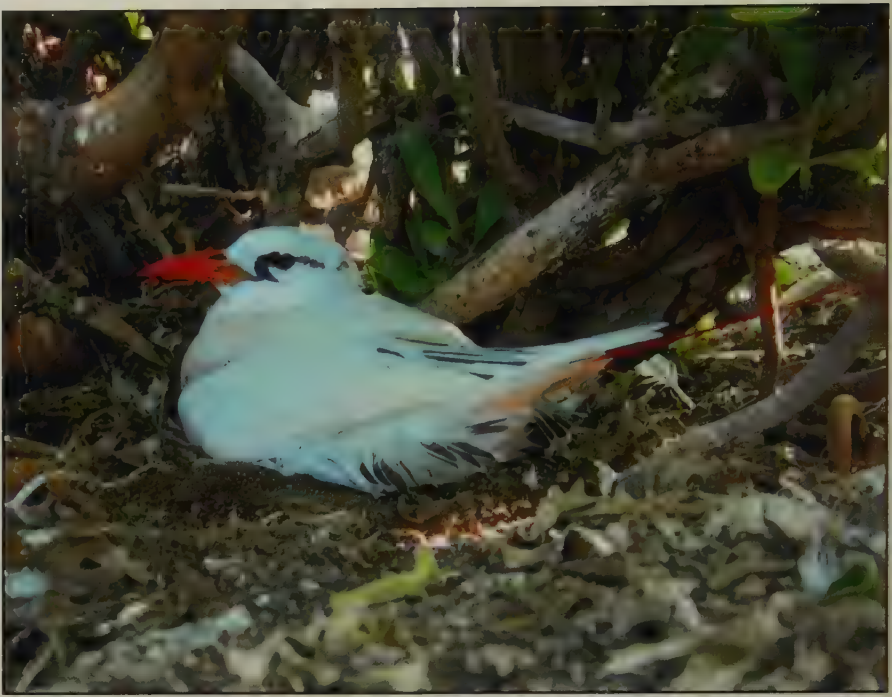


Figure 7.30. Red-tailed Tropicbird, Tern Island, French Frigate Shoals. Photo: C. Gregory.

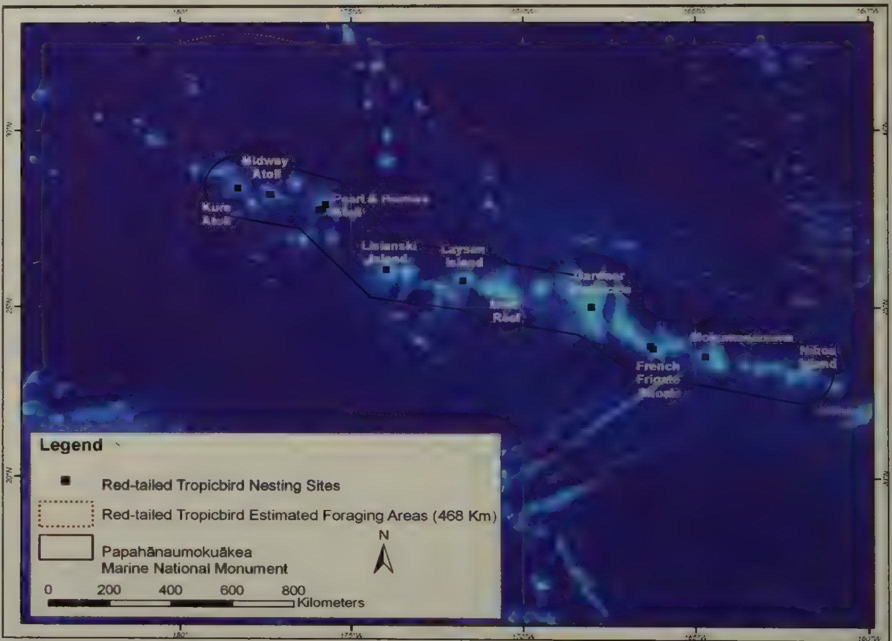


Figure 7.31. Red-tailed Tropicbird nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

White-Tailed Tropicbird (*Phaethon lepturus dorothea*)

White-tailed Tropicbirds are similar in appearance to Red-tailed Tropicbirds, but are smaller and more slender, with a total length of 60-80 cm (including the central rectrices), a wingspan of 90-95 cm, and a mean body mass of 350 g (Lee and Walsch-Mcgehee, 1998). As with Red-tailed Tropicbirds, body plumage is white, often with a pink wash, but the long central rectrices are white, and the bill is more orange than red (Lee and Walsch-Mcgehee, 1998; Figure 7.32).

White-tailed Tropicbirds range throughout the tropics with the exception of the eastern Pacific and northeastern Atlantic. The largest colonies in the Pacific occur on American Samoa and the MHI. Smaller colonies are found at Midway Atoll, Palmyra, Wake and the Marianas (USFWS, 2005). Within the NWHI, White-tailed Tropicbirds nest only at Midway Atoll, where a few pairs may breed throughout the year (Figure 7.33). White-tailed Tropicbirds may be competitively excluded from other islands in the northwestern chain by Red-tailed Tropicbirds; in areas of sympatry, the larger Red-tailed Tropicbirds do often outcompete White-tails for nest sites (Harrison, 1990).

White-tailed Tropic birds forage at distances up to 120 km from nesting colonies (USFWS, 2005; Figure 7.33), such that the foraging range extends beyond the boundaries of the Monument. The species are solitary, plunge divers and feed mainly on flying fish without aggregations into multi-species feeding flocks with other seabirds.

Introduced predators are the greatest threat throughout the breeding range.

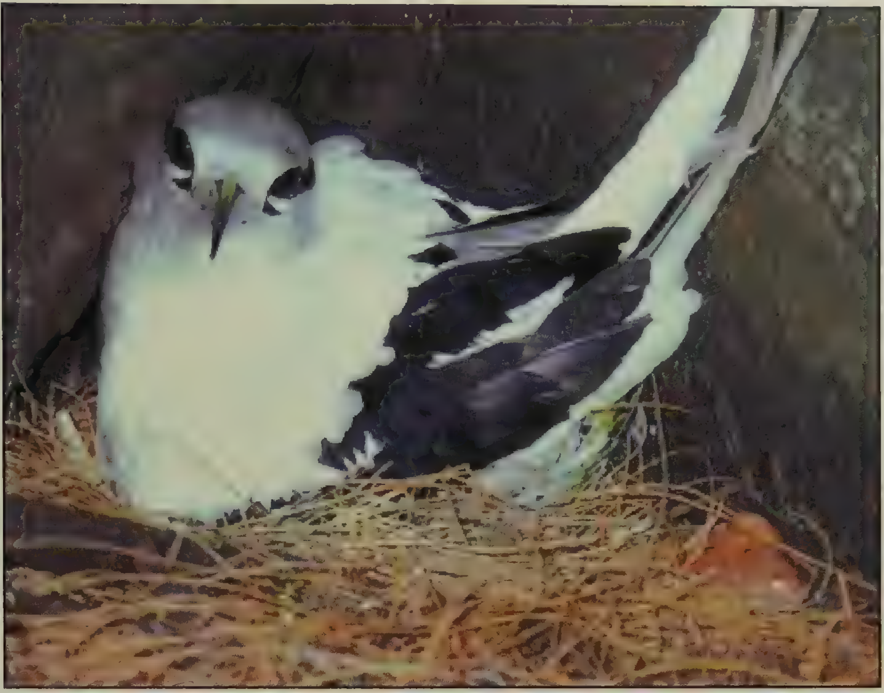


Figure 7.32. White-tailed Tropicbird, Sand Island, Midway Atoll. Photo: K. Starr.

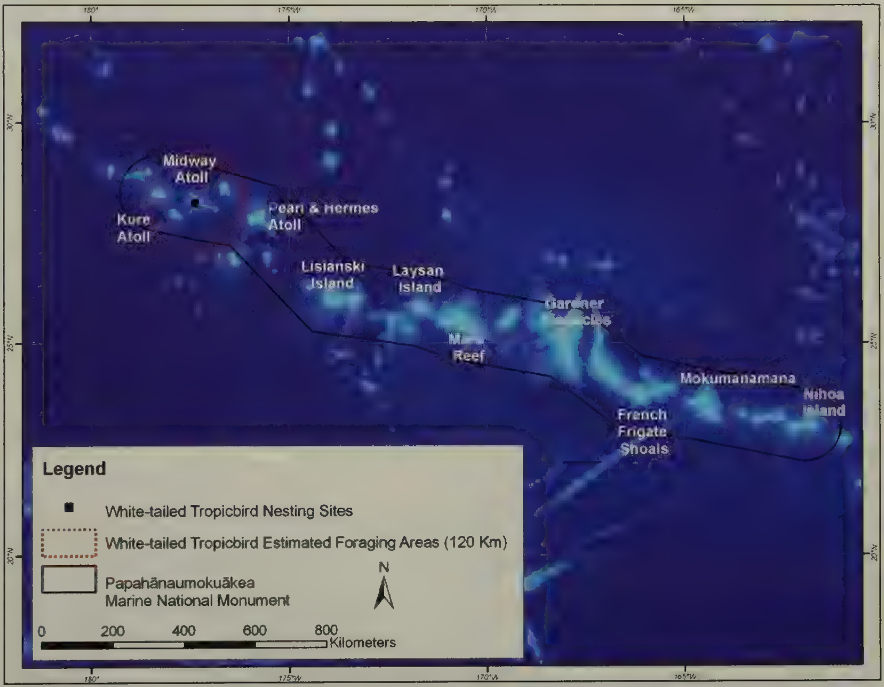


Figure 7.33. White-tailed Tropicbird nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

CHARADRIIFORMES (TERNS AND NODDIES)

Black Noddy (*Anous minutus marcusi*)

The Black Noddy is similar in appearance to the Brown Noddy, but with a smaller body size (length 35-40 cm, and body mass 85-140 g), and darker brown plumage throughout. The head is gray-brown, fading to grayish-white on the forehead, and with a white crescent on the lower eye. The bill is black, and legs and feet are reddish brown to orange (Gauger, 1999; Figure 7.34).

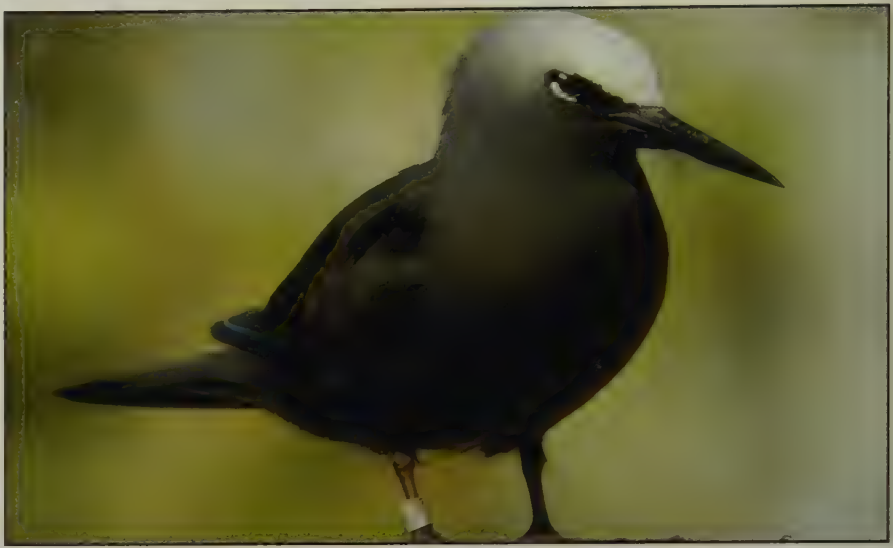


Figure 7.34. Black Noddy, Tern Island, French Frigate Shoals. Photo: C. Gregory.

Black Noddies are a pantropical species, and the largest colonies in the NWHI are at Midway Atoll and Nihoa Island (USFWS, 2005; Figure 7.35). In the NWHI, Black Noddies can breed year around, but in general eggs are laid between October and June, and chicks are present from December to August.

Breeding adults forage within 80 km of nesting colonies and often forage near shore <10 fm (USFWS, 2005; Figure 7.35). Black Noddies feed by surface dipping, and prey species include juvenile and larval goatfish, lizardfish, herring, flying fish and gobies.

Habitat loss, predation, invasive species and disturbance are all threats to Black Noddy populations. Introduced insects at Kure Atoll and increases in the invasive golden crown-beard have had negative impacts on nesting habitat (USFWS, 2005).

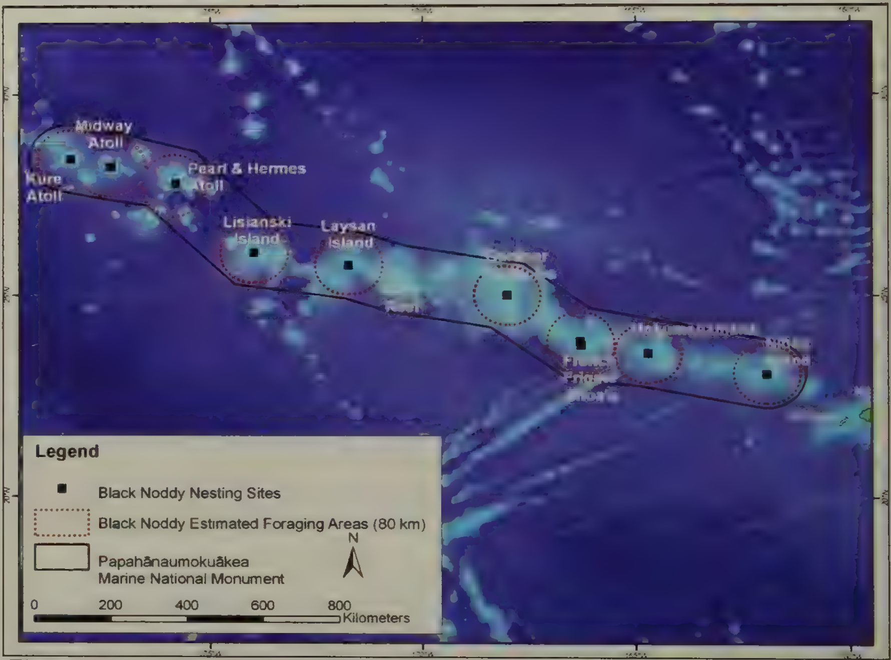

Midway Atoll
Kure Atoll
Pearl & Hermes Atoll
Lisianski Island
Laysan Island
Legend
Black Noddy Nesting Sites
Black Noddy Estimated Foraging Areas (80 km)
Papahānaumokuākea Marine National Monument
N
0
200
400
600
800
Kilometers

Figure 7.35. Black Noddy nesting sites and foraging areas in the NWHI. Source: USFWS, 2005; map: K. Keller.

Brown Noddy (*Anous stolidus pileatus*)

Brown Noddies are a medium-sized tern species; they are slightly larger than Black Noddies, with a length of 40-45 cm and a mean body mass of 180 g. Body plumage is chocolate-brown throughout, with a gray-brown head, grayish-white forehead, and white eye ring. The bill is black, and legs and feet are dark gray to black (Chardine and Morris, 1996; Figure 7.36).

Brown Noddies are a pantropical species, with breeding colonies occurring at American Samoa, the Marianas, Johnston Atoll and the NWHI. The largest colony in the NWHI is on Nihoa Island (USFWS, 2005; Figure 7.37). In the NWHI, females lay eggs between January and May, and chicks are present from February to November.

Foraging during the breeding season occurs within sight of the nesting colonies. During the nonbreeding season, the birds are known to stay within 100 km of the nesting colonies (USFWS, 2005; Figure 7.37). Brown Noddies feed by surface dipping, and prey includes goatfish, lizardfish, mackerel scad, flying fish and squid. (USFWS, 2005)

Predators are the greatest threat to Brown Noddy populations.

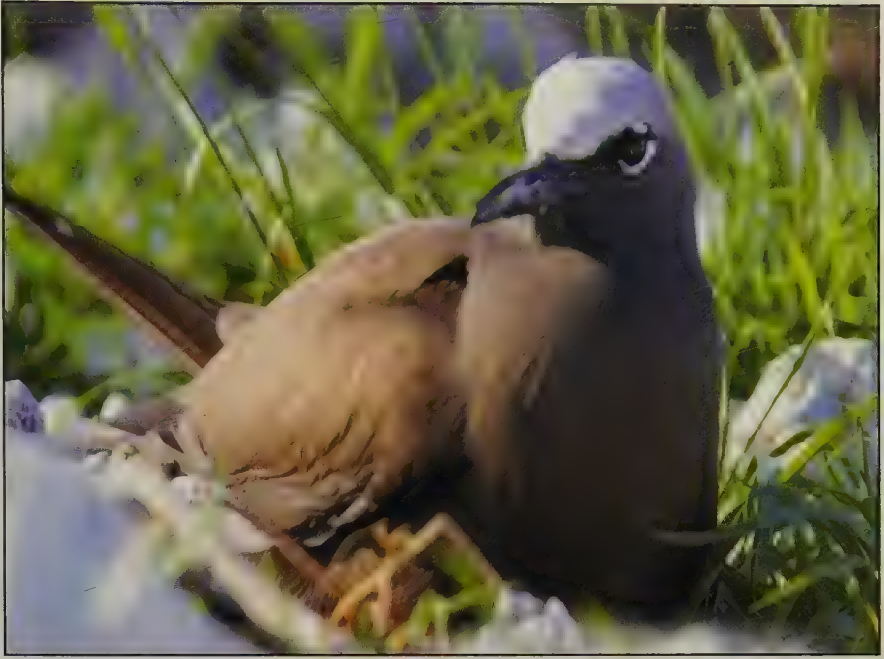


Figure 7.36. Brown Noddy, Tern Island, French Frigate Shoals. Photo: NOAA.

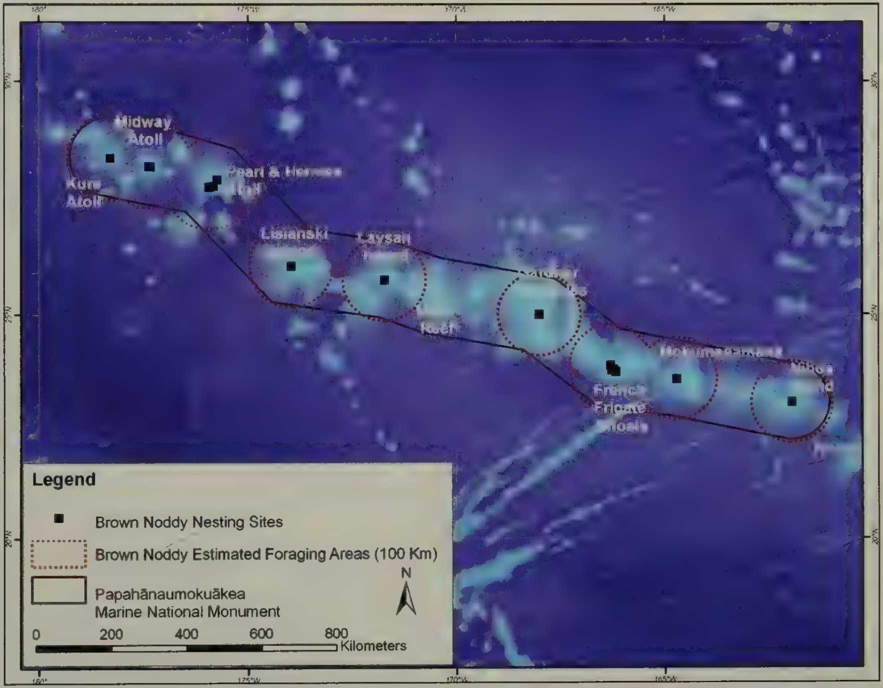


Figure 7.37. Brown Noddy nesting sites and foraging areas in the NWHI. Source: USFWS, 2005; map: K. Keller.

Blue Noddy of Blue-Gray Noddy (*Procelsterna cerulea saxatilis*)

The Blue Noddy is the world's smallest tern species. Body plumage is bluish-gray throughout, with slightly lighter coloration on the head and ventral surfaces, and a white eye ring. Primaries and tail are dark gray. Bill and legs dark gray, and feet are gray with yellow-gray webbing (http://www.state.hi.us/dlnr/dofaw/cwcs/Conservation_need.htm#Species; A. Anders, pers. obs.; Figure 7.38).

Blue Noddies are found throughout the Pacific, with the largest nesting colonies on Nihoa Island and Mokumanamana (USFWS, 2005). Blue Noddies nest in the eastern portion of the NWHI on Nihoa Island, Mokumanamana, French Frigate Shoals (on La Perouse Pinnacle) and Gardner Pinnacles (Figure 7.39). On these islands, Blue Noddies lay eggs between January and May, and chicks are present from January to June. There is some variation in breeding times between islands. The species is generally considered a year-round resident to the Hawaiian Islands.

Blue Noddies feed by surface dipping and feed mainly on larval lizardfishes, flounders, goatfishes and flying fish. They have also been known to take squid, crustaceans and halobates (USFWS, 2005).

Natural predators are the main threat to blue noddies.

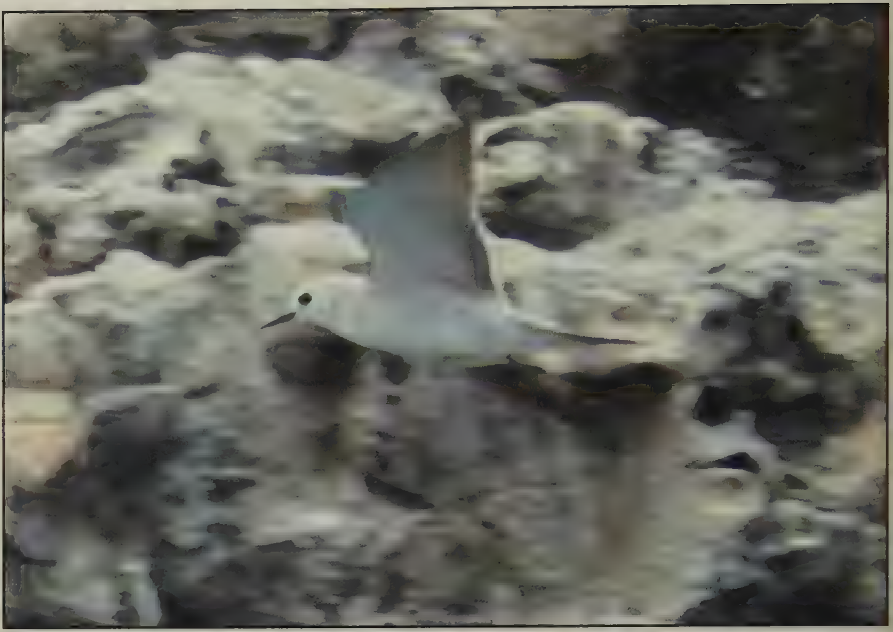


Figure 7.38. Blue Noddy, La Perouse Pinnacle, French Frigate Shoals. Photo: D. Wright.

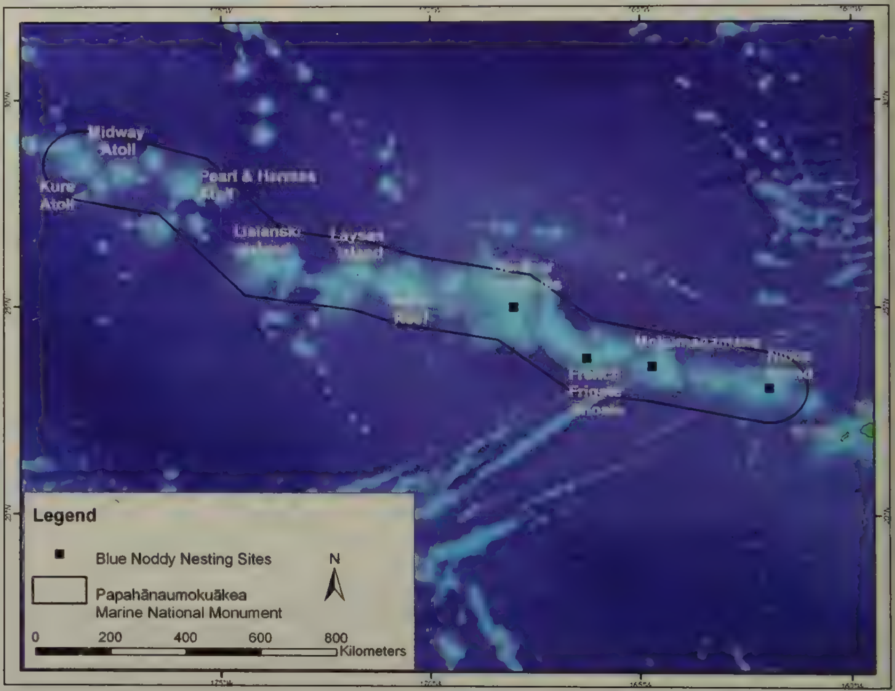


Figure 7.39. Blue Noddy nesting sites in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

White Tern (*Gygis alba alba*)

White Terns are a medium-sized tern species, with a length of 27-33 cm, wingspan of 70-87 cm, and body mass of 77-157 g. Body plumage is entirely white, with a black eye ring. The bill is black, and legs and feet are gray-blue with yellow-white webs (Niethammer and Patrick, 1998; Figures 7.40).

The White Tern is a pantropical species, with the largest colonies in the NWHI occurring on Nihoa Island and Midway Atoll (Figure 7.41). Other islands including American Samoa and the Marianas also support large populations (USFWS, 2005). In the NWHI the species breeds year-around.

White Terns forage in near-shore waters during the breeding season. The species forages by surface diving, plunging and dipping. Prey includes juvenile goatfish and flying fish, while a smaller portion of the diet is composed of squid, needlefishes, halfbeaks, dolphinfishes and blennies (USFWS, 2005).

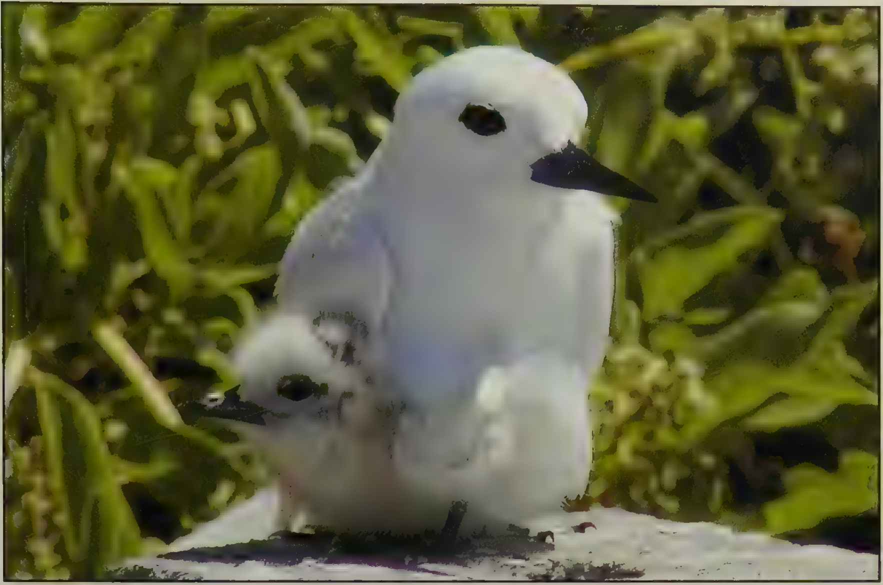


Figure 7.40. White Tern with chick, Tern Island, French Frigate Shoals. Photo: NOAA.

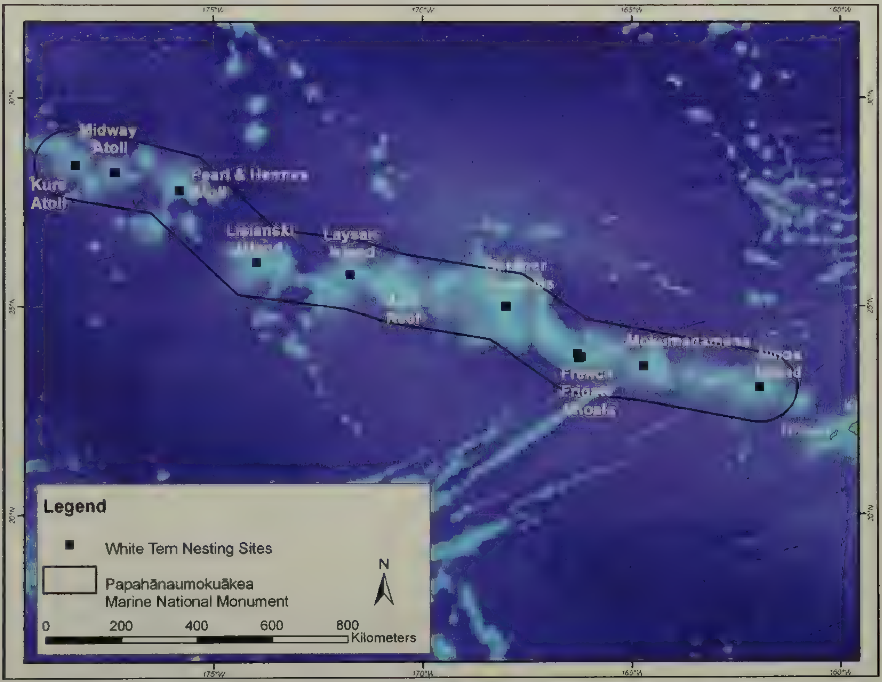


Figure 7.41. White Tern nesting sites in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Sooty Tern (*Sterna fuscata oahuensis*)

The Sooty Tern is a medium-sized tern species, with a length of 36-45 cm, a wingspan of 82-94 cm, and mean body mass of 200 g (Schreiber et al., 2002). Body plumage is deep black dorsally and on the tail, with a highly-contrasting white face, throat, and underbelly. A white patch on the forehead extends to just above the eye, creating a black eyeline. The bill, legs, and feet are black (Schreiber et al., 2002; Figure 7.42).

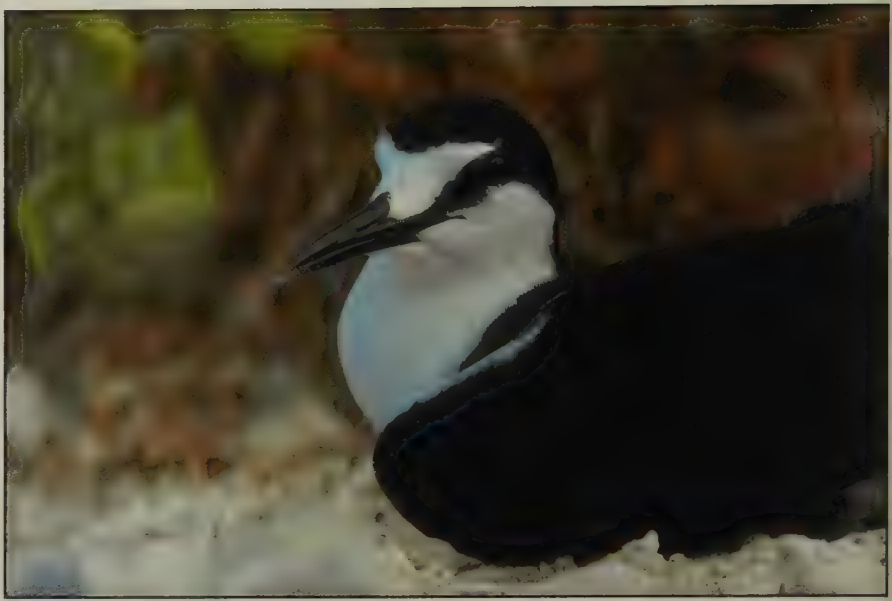


Figure 7.42. A Sooty Tern at Tern Island, French Frigate Shoals. Photo: C. Gregory.

Sooty Terns are a pantropical species. The largest colonies in the NWHI occur at Laysan Island and Lisianski Island. Baker and Jarvis support equally large populations (USFWS, 2005; Figure 7.43). Sooty Terns breed on all islands and atolls in the NWHI, with eggs laid between March and July and chicks present from April to September.

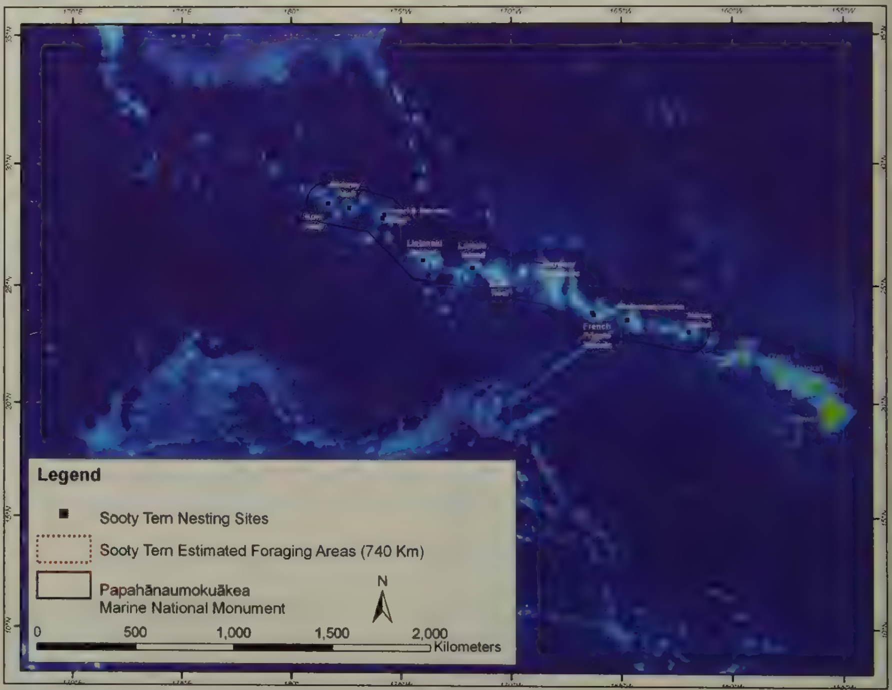

Legend
■ Sooty Tern Nesting Sites
Sooty Tern Estimated Foraging Areas (740 Km)
Papahānaumokuākea Marine National Monument
N
0
500
1,000
1,500
2,000
Kilometers
Lisianski
French Frigate

Figure 7.43. Sooty Tern nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Sooty Tern foraging distances have been calculated to be 740 km (USFWS, unpublished data) during the breeding season and 5,000 km during nonbreeding season (Figure 7.43). Sooty Terns feed by surface dipping, and main prey species include squid, goatfish, flying fish and mackerel scad (USFWS, 2005).

Introduced predators are a major threat to Sooty Terns. While rats have been eradicated from the NWHI, cattle egrets continue to take chicks at Midway Atoll (USFWS, 2005). In addition to introduced predators, native predators such as Great Frigatebirds and Laysan Finches also prey on Sooty Tern eggs and chicks.

Gray-Backed Tern (*Sterna lunata*)

Gray-backed Terns are a medium-sized Tern, with a length of 35-38 cm and body mass of 95-145 g. The upper wings, back, and tail are slate-gray, and the throat, belly, and underwings are white. The head is white with a full black cap and black eyeline, and the bill, legs, and feet are black (Mostello et al., 2000; Figure 7.44).

Gray-backed Terns are found in the tropical and subtropical Pacific, with the largest breeding colonies at Lisianski Island, Nihoa Island and Laysan Island. Smaller colonies are found on Johnston, Wake and Jarvis (USFWS, 2005). Gray-backed Terns nest on all islands and atolls in the NWHI, with eggs laid from March to July, and chicks present from April to September (Figure 7.45).

Gray-back Terns have been estimated to forage up to 370 km from land, which includes areas outside of the Monument (USFWS, 2005; Figure 7.45). Gray-backed Terns feed by hovering and dipping; prey species include five-horned cowfish, juvenile flying fish, goatfish, herring and dolphinfish. Additional prey include squid, crustaceans, mollusks, and marine and terrestrial insects (USFWS, 2005).

As with other seabird species, habitat destruction and disturbance are the greatest threats to this species in the NWHI (USFWS, 2005).

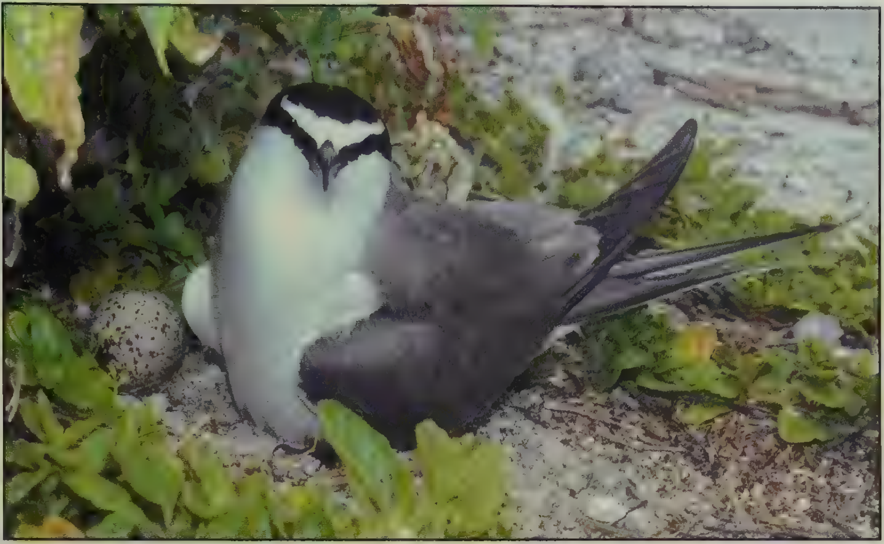


Figure 7.44. Gray-backed Tern. Photo: F. Starr.

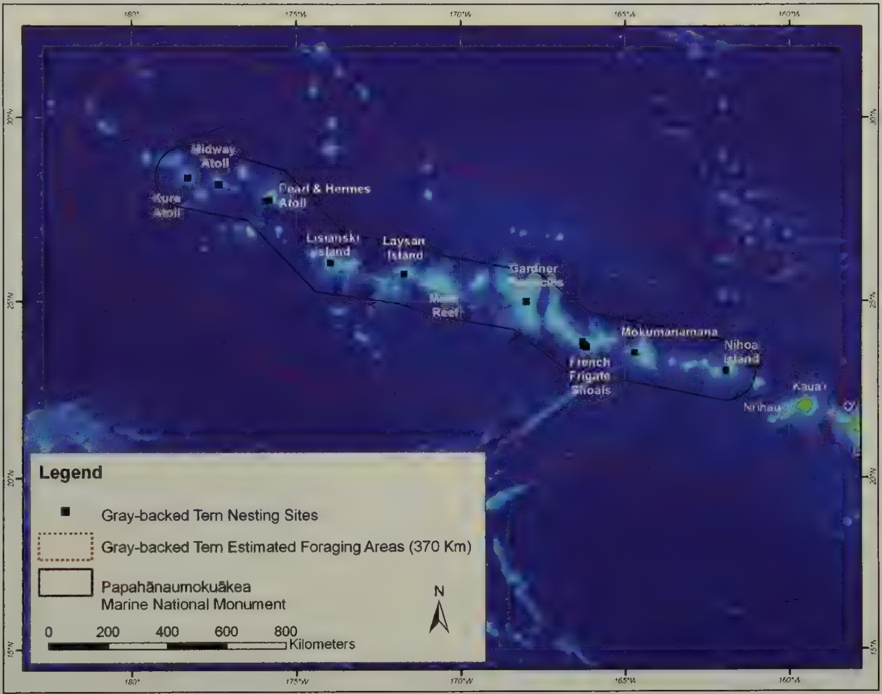


Figure 7.45. Gray-backed Tern nesting sites and foraging areas in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

Little Tern (*Sterna albifrons sinensis*)

The distribution of Little Terns (Figure 7.46) is pantropical; however, populations in the NWHI are very small and have been found only at Pearl and Hermes and Midway Atolls (USFWS, 2005), and French Frigate Shoals (A. Anders, pers. comm.; Figure 7.47). Little Terns breed in the spring.

During the breeding season, the species stays within 3 km of the breeding colonies while foraging. Little Terns are shallow-water plunge divers, with a diet consisting of small fish, crustaceans, insects, annelids and mollusks (USFWS, 2005).

Habitat destruction and disturbance are two of the threats faced by Little Terns. The breeding-season foraging range is completely protected within the boundaries of the Monument.

Figure 7.46. Little Tern. Photo: D. Mason, www.realbirder.com.

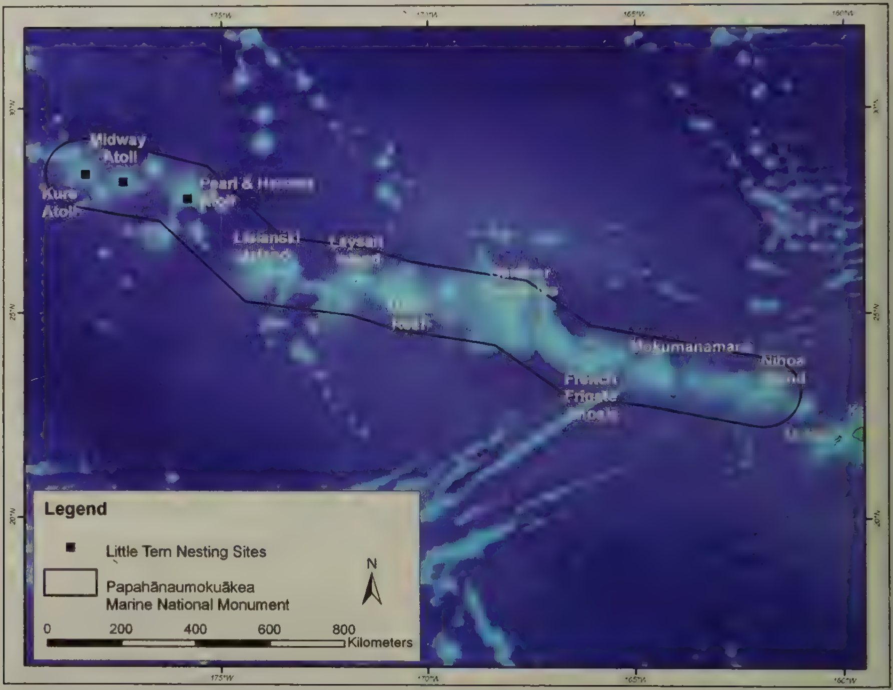


Figure 7.47. Little Tern nesting sites in the NWHI. Source: USFWS, unpub. data; map: K. Keller.

POPULATION STATUS AND TRENDS

Available Data

Large-scale monitoring of seabird populations in the NWHI began in the early 1960s, with the Smithsonian Institution's Pacific Ocean Biological Survey Program (POBSP). This program was followed by Tripartite Cooperative Agreement Studies in the late 1970s and early 1980s, and by the current long-term monitoring program initiated in 1980 by the USFWS at French Frigate Shoals, Midway Atoll and Laysan Island. The current USFWS seabird monitoring program provides information on seabird populations over time within French Frigate Shoals, Midway and Laysan, but geographical comparisons are difficult, as data collection methods have differed across these locations.

Pacific Ocean Biological Survey Program

The POBSP was conducted throughout the Pacific by the Smithsonian Institution from 1963-1970. The Smithsonian's surveys included at-sea bird observations, as well as breeding population counts and banding on islands and atolls within the NWHI from 1963-1968 (King, 1974). The resulting data provide a general baseline for five species of seabirds that breed on Nihoa, Mokumanamana, French Frigate Shoals, Lisianski, Laysan, Pearl and Hermes Atoll, Midway Atoll and Kure Atoll, including Laysan and Black-footed Albatrosses, Wedge-tailed Shearwaters, Red-tailed Tropicbirds and Sooty Terns (Table 7.4). Because the POBSP breeding population size data presented in King (1974) were not well documented in terms of the types and timing of the counts, it is not entirely clear if population estimates were total number of individuals or number of breeding pairs. It is thus difficult to compare the 1960s data to current population size estimates. However, the POBSP data do allow for general comparisons of population sizes between islands and atolls for the time period during which those data were collected (Table 7.5).

Table 7.4. Smithsonian Institution Pacific Ocean Biological Survey Program Survey Sites.

SITE	**BLACK-FOOTED ALBATROSS** *(Phoebastria nigripes)*	**LAYSAN'S ALBATROSS** *(Phoebastria immutabilis)*	**RED-TAILED TROPICBIRD** *(Phaethon rubricauda rothschildi)*	**SOOTY TERN** *(Sterna fuscata oahuensis)*	**WEDGE-TAILED SHEARWATER** *(Puffinus pacificus chlororhynchus)*
French Frigate Shoals	X	X	X	X	X
Kure	X	X	X	X	X
Laysan	X	X	X	X	X
Lisianski	X	X	X	X	X
Midway	X	X	X	X	X
Mokumanamana	X	X	X	X	X
Nihoa	X	X	X	X	X
Pearl and Hermes	X	X	X	X	X

Table 7.5. POBSP Seabird Population Survey Results.

SITE	SPECIES	SCIENTIFIC NAME	COMMON NAME	DATE	LOW VALUE	HIGH VALUE	UNITS
Lisianski	LAAL	*Phoebastria immutabilis*	Laysan Albatross	1963-1968	8,000	10,000	Largest number of breeders
Nihoa	LAAL	*Phoebastria immutabilis*	Laysan Albatross	1963-1968	--	38	Largest number of breeders
Kure	LAAL	*Phoebastria immutabilis*	Laysan Albatross	1963-1968	--	3,200	Largest number of breeders
MMM	LAAL	*Phoebastria immutabilis*	Laysan Albatross	1963-1968	--	1,650	Largest number of breeders
FFS	LAAL	*Phoebastria immutabilis*	Laysan Albatross	1963-1968	--	1,000	Largest number of breeders
Midway	LAAL	*Phoebastria immutabilis*	Laysan Albatross	1963-1968	--	110,000	Largest number of breeders
Laysan	LAAL	*Phoebastria immutabilis*	Laysan Albatross	1963-1968	300,000	500,000	Largest number of breeders
Pearl and Hermes	LAAL	*Phoebastria immutabilis*	Laysan Albatross	1963-1968	--	30,000	Largest number of breeders
MMM	BFAL	*Phoebastria nigripes*	Black-footed Albatross	1963-1968	--	375	Maximum number of breeding birds recorded
FFS	BFAL	*Phoebastria nigripes*	Black-footed Albatross	1963-1968	--	3,100	Maximum number of breeding birds recorded
Laysan	BFAL	*Phoebastria nigripes*	Black-footed Albatross	1963-1968	--	40,000	Maximum number of breeding birds recorded
Nihoa	BFAL	*Phoebastria nigripes*	Black-footed Albatross	1963-1968	--	100	Maximum number of breeding birds recorded
Lisianski	BFAL	*Phoebastria nigripes*	Black-footed Albatross	1963-1968	--	4,000	Maximum number of breeding birds recorded
Pearl and Hermes	BFAL	*Phoebastria nigripes*	Black-footed Albatross	1963-1968	--	9,000	Maximum number of breeding birds recorded
Midway	BFAL	*Phoebastria nigripes*	Black-footed Albatross	1963-1968	--	24,000	Maximum number of breeding birds recorded
Kure	BFAL	*Phoebastria nigripes*	Black-footed Albatross	1963-1968	--	1,150	Maximum number of breeding birds recorded
MMM	WTSH	*Puffinus pacificus chlororhynchus*	Wedge-tailed Shearwater	1963-1968	--	2,000	Maximum number recorded
Kure	WTSH	*Puffinus pacificus chlororhynchus*	Wedge-tailed Shearwater	1963-1968	--	6,230	Maximum number recorded
MMM	SOTE	*Sterna fuscata oahuensis*	Sooty Tern	1968	--	50,000	Maximum number recorded
Midway	SOTE	*Sterna fuscata oahuensis*	Sooty Tern	1968	--	353,000	Maximum number recorded
Laysan	SOTE	*Sterna fuscata oahuensis*	Sooty Tern	1968	--	2,000,000	Maximum number recorded
Nihoa	SOTE	*Sterna fuscata oahuensis*	Sooty Tern	1968	--	100,000	Maximum number recorded
Pearl and Hermes	WTSH	*Puffinus pacificus chlororhynchus*	Wedge-tailed Shearwater	1963-1968	--	22,400	Maximum number recorded
Laysan	WTSH	*Puffinus pacificus chlororhynchus*	Wedge-tailed Shearwater	1963-1968	--	200,000	Maximum number recorded
FFS	SOTE	*Sterna fuscata oahuensis*	Sooty Tern	1968	--	250,000	Maximum number recorded
Pearl and Hermes	SOTE	*Sterna fuscata oahuensis*	Sooty Tern	1968	--	40,110	Maximum number recorded
Nihoa	WTSH	*Puffinus pacificus chlororhynchus*	Wedge-tailed Shearwater	1963-1968	--	25,000	Maximum number recorded
Kure	SOTE	*Sterna fuscata oahuensis*	Sooty Tern	1968	--	48,000	Maximum number recorded
Lisianski	WTSH	*Puffinus pacificus chlororhynchus*	Wedge-tailed Shearwater	1963-1968	--	60,000	Maximum number recorded
Lisianski	SOTE	*Sterna fuscata oahuensis*	Sooty Tern	1968	--	1,000,000	Maximum number recorded
Midway	WTSH	*Puffinus pacificus chlororhynchus*	Wedge-tailed Shearwater	1963-1968	--	3,000	Maximum number recorded

Table 7.5. (continued). POBSP Seabird Population Survey Results.

SITE	SPECIES	SCIENTIFIC NAME	COMMON NAME	DATE	LOW VALUE	HIGH VALUE	UNITS
Nihoa	RTTR	*Phaethon rubricauda rothschildi*	Red-tailed Tropicbird	1963-1968	--	500	Maximum population estimates
Kure	RTTR	*Phaethon rubricauda rothschildi*	Red-tailed Tropicbird	1963-1968	--	2,500	Maximum population estimates
MMM	RTTR	*Phaethon rubricauda rothschildi*	Red-tailed Tropicbird	1963-1968	--	200	Maximum population estimates
FFS	RTTR	*Phaethon rubricauda rothschildi*	Red-tailed Tropicbird	1963-1968	--	225	Maximum population estimates
Laysan	RTTR	*Phaethon rubricauda rothschildi*	Red-tailed Tropicbird	1963-1968	--	4,000	Maximum population estimates
Pearl and Hermes	RTTR	*Phaethon rubricauda rothschildi*	Red-tailed Tropicbird	1963-1968	--	165	Maximum population estimates
Lisianski	RTTR	*Phaethon rubricauda rothschildi*	Red-tailed Tropicbird	1963-1968	--	3,000	Maximum population estimates
Midway	RTTR	*Phaethon rubricauda rothschildi*	Red-tailed Tropicbird	1963-1968	--	7,500	Maximum population estimates

Island/atoll abbreviations: MMM = Mokumanamana, FFS = French Frigate Shoals

Species abbreviations: LAAL = Laysan's Albatross; BFAL = Black-footed Albatross; WTSH = Wedge-tailed Shearwater; SOTE = Sooty Tern; WTSH = Wedge-tailed Shearwater; RTTR = Red-tailed Tropicbird

Tripartite Cooperative Agreement Studies

In 1975, the National Marine Fisheries Service, USFWS, and Hawaii Division of Aquatic Resources (then known as Division of Fish and Game) established a five-year Tripartite Cooperative Agreement to conduct surveys and assessments of the NWHI (Grigg and Tanoue, 1984). One of the publications resulting from this cooperative agreement included a summary of the seabird research that had been conducted in the northwestern islands, and included information on 18 species of seabirds that breed in the northwestern chain. From 1978 to 1982, USFWS conducted field studies of variable length (from five weeks to year-around) at Nihoa Island, French Frigate Shoals, Laysan Island and Lisianski Island. In addition, short field trips were conducted to most of the other islands and atolls, but these shorter trips did not produce detailed population evaluations. The data presented in the Tripartite Cooperative Agreement Studies report is a combination of POBSP data and the field data collected from 1978–1982. The report is limited in use for biogeographic comparisons between islands/atolls because the dates and methods of data collection were not reported, but it is possible to use the data as a baseline for seabird breeding population sizes within islands and atolls (Fefer et al., 1984).

USFWS Seabird Monitoring Program

The USFWS has been conducting seabird monitoring at French Frigate Shoals and Midway Atoll since 1980. Various levels of population monitoring have been conducted at French Frigate Shoals for each of the following species: Laysan Albatrosses, Black-footed Albatrosses, Bonin Petrels, Bulwer's Petrels, Wedge-tailed Shearwaters, Christmas Shearwaters, Tristram's Storm-petrels, Red-footed Boobies, Masked Boobies, Great Frigatebirds, Red-tailed Tropicbirds, Black Noddies, Brown Noddies, White Terns and Gray-backed Terns. Monitoring at Laysan Island also occurs once a year, where data are collected on Laysan Albatrosses, Black-footed Albatrosses, Red-footed Boobies and Great Frigatebirds (data from 1992-present are currently available). As time and funding allow, periodic monitoring also occurs on the other islands and atolls in the NWHI. The long-term data sets from French Frigate Shoals, Midway Atoll and Laysan Island provide information about the variability of the seabird populations within each of those islands/atolls over the past 27 years, but because monitoring methods have differed between locations, inter-island or-atoll comparisons for biogeographic assessment are limited. As a first step toward future biogeographic analysis, data layers of presence and absence of species are presented here, as are a subset of results from the long-term seabird monitoring program at French Frigate Shoals and Midway Atoll. Table 7.5 also indicates the types of monitoring data that have been collected at each island and atoll.

USFWS Monitoring at French Frigate Shoals

Methods

Since 1980, the USFWS has conducted field monitoring on Tern Island, French Frigate Shoals, to estimate the minimum number of breeding pairs and annual reproductive success of a subset of the seabird species that breed on the island. Beginning in 1980-1981, minimum numbers of breeding pairs and reproductive success were estimated annually for Laysan and Black-footed Albatrosses, Red-footed Boobies, Red-tailed Tropicbirds, Black Noddies, and White Terns (Dearborn et al., 2001). USFWS has since expanded the monitoring program on Tern Island, such that minimum numbers of breeding pairs are now estimated annually, as of 2008, for Laysan Albatrosses, Black-footed Albatrosses, Christmas Shearwaters, Bulwer's Petrels, Tristram's Storm-petrels, Red-footed Boobies, Masked Boobies, Great Frigatebirds, Red-tailed Tropicbirds, Black Noddies, Brown Noddies, White Terns and Gray-backed Terns (USFWS, 2008). In addition, annual reproductive success is now monitored for Laysan and Black-footed Albatrosses, Bulwer's Petrels, Tristram's Storm-petrels, Red-footed Boobies, Masked Boobies, Red-tailed Tropicbirds and Black Noddies (USFWS, 2008).

Estimation of the minimum number of pairs breeding on Tern Island varies by species, depending primarily upon population size and the level of breeding synchrony exhibited by the species. For the Procellariiformes, including Laysan and Black-footed Albatrosses, Christmas Shearwaters, Bulwer's Petrels, and Tristram's Storm-petrels, population sizes are relatively small, and breeding synchrony is high. For these reasons, the number of breeding pairs nesting on Tern Island are counted directly each year for each of these species (numbers of breeding pairs of Laysan and Black-footed Albatrosses are also directly counted each year at all other islands within French Frigate Shoals, such that the number of breeding pairs for the entire atoll can be estimated for these two species). In contrast, breeding within the Pelecaniformes and Charadriiformes species is highly asynchronous, and population sizes are larger, such that direct counts of breeding pairs are not possible (with the exception of Masked Boobies, for which all breeding adults on Tern Island are banded, and the breeding population consists of only a few hundred pairs; A. Anders, pers. comm.). For these species, estimates of the minimum numbers of breeding pairs are based upon mean incubation count nest censuses: for each species, a count of all nests at which an adult is incubating is conducted at a periodicity that equals the mean incubation length for that species. For example, the mean incubation length of Great Figatebirds is 55 days, so a count of all nests at which an egg is being incubated is conducted every 55 days (USFWS, 2008). Summing the mean incubation counts over an entire year then provides information on the minimum number of breeding pairs that attempted to nest in that year (the estimate is a minimum, as some nests are initiated and fail between mean incubation count periods, so these failed breeding pairs are not counted; there is also some error introduced by the fact that within some species, individuals or breeding pairs may attempt to re-nest after nest failure within a year).

Finally, annual reproductive success is also monitored based upon species' population sizes and level of breeding synchrony. For Laysan Albatrosses, Black-footed Albatrosses, Bulwer's Petrels, Tristram's Storm-petrels, Masked Boobies, White Terns, and Gray-backed Terns, breeding populations are small enough and/or breeding is synchronous enough that virtually all nests on Tern Island are monitored to obtain an annual estimate of nesting success. In contrast, for Red-footed Boobies, Red-tailed Tropicbirds, and Black Noddies, nests are monitored year-around within multiple randomly-chosen permanent plots on Tern Island, with all nests in all plots being checked every two to four days for failure, hatching, or fledging (Dearborn and Anders, 1996). For each of these species, the reproductive success plots include approximately 20-30% of all nests on Tern Island for that particular species (Dearborn et al., 2001). Randomly-chosen permanent nest monitoring plots were also set up for Laysan and Black-footed Albatrosses beginning in 2006, in order to obtain more precise estimates of nesting success on Tern Island for these two species (USFWS, 2008; A. Anders, pers. comm.). For all species, nest monitoring methods provide data for annual estimates of hatching success, fledging success, and overall reproductive success for each species monitored. Estimates of minimum numbers of breeding pairs and for hatching, fledging, and overall reproductive success are available for all monitored species from 1996 through the present from the Pacific Seabird Monitoring Database (Pacific Seabird Group and USGS, Alaska Biological Science Center, 2007).

Results

The following figures (Figure 7.48) indicate the minimum numbers of breeding pairs of Laysan Albatrosses and Black-footed Albatrosses each year at all islands within French Frigate Shoals from 1960 – 2007 (1962 data: Rice and Kenyon, 1962; 1960-1983 data: Harrison et al., 1983; 1980-2007 data: Pacific Seabird Group and USGS, 2007). For both species, breeding population size varies annually, but both species have exhibited population increases at French Frigate Shoals since 2004.

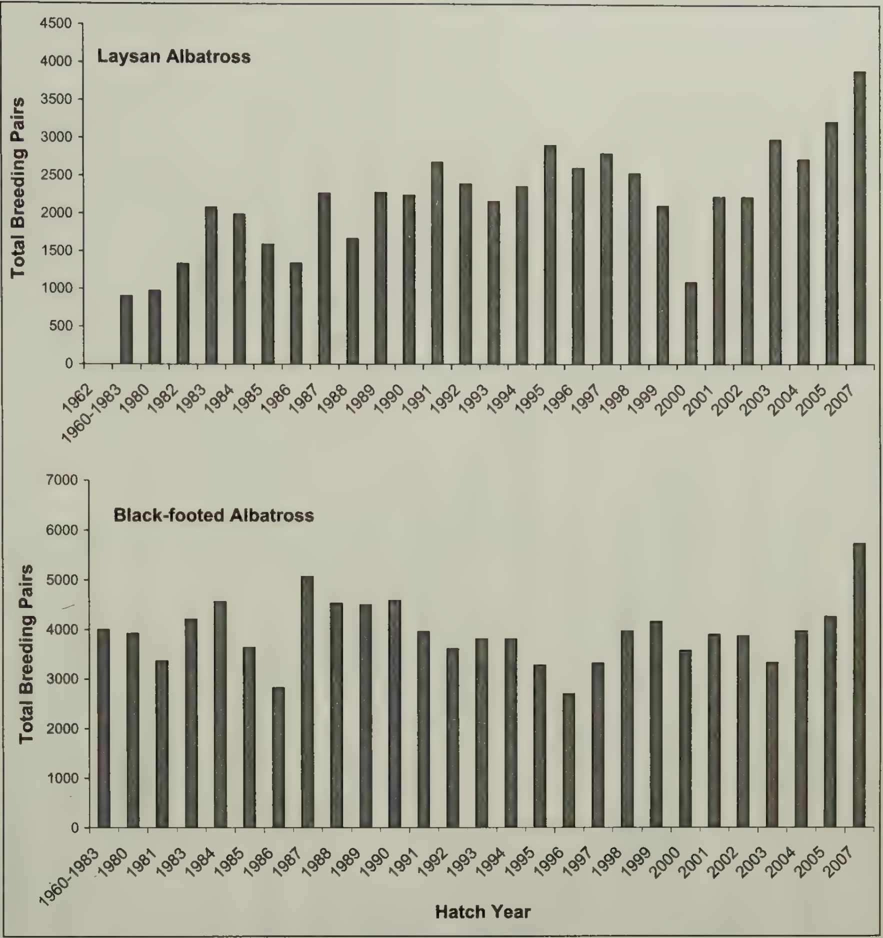


Figure 7.48. The minimum numbers of breeding pairs of Laysan Albatrosses and Black-footed Albatrosses each year at all islands within French Frigate Shoals from 1960 – 2007. Sources: Rice and Kenyon, 1962; Harrison, 1983; Pacific Seabird Monitoring Database, 2008.

Estimates of the minimum numbers of breeding pairs on Tern Island, French Frigate Shoals are presented in Figure 7.49 for Bulwer's Petrels, Christmas Shearwaters, Red-footed Boobies, Masked Boobies, Red-tailed Tropicbirds, Great Frigatebirds, Black Noddies, Brown Noddies, White Terns and Gray-backed Terns from 1996 – 2006 (Pacific Seabird Monitoring Database, 2008). In 2006, Bulwer's Petrel nest boxes were temporarily relocated during building construction on Tern Island, such that only natural crevices were available for nesting for this species in that year. The number of Christmas Shearwater breeding pairs appears to have declined in 2002-2006 relative to 1996-2001, and numbers of Masked Booby breeding pairs increased steadily over the 11-year period shown. All other species' breeding population sizes have fluctuated annually or remained stable from 1996-2006.

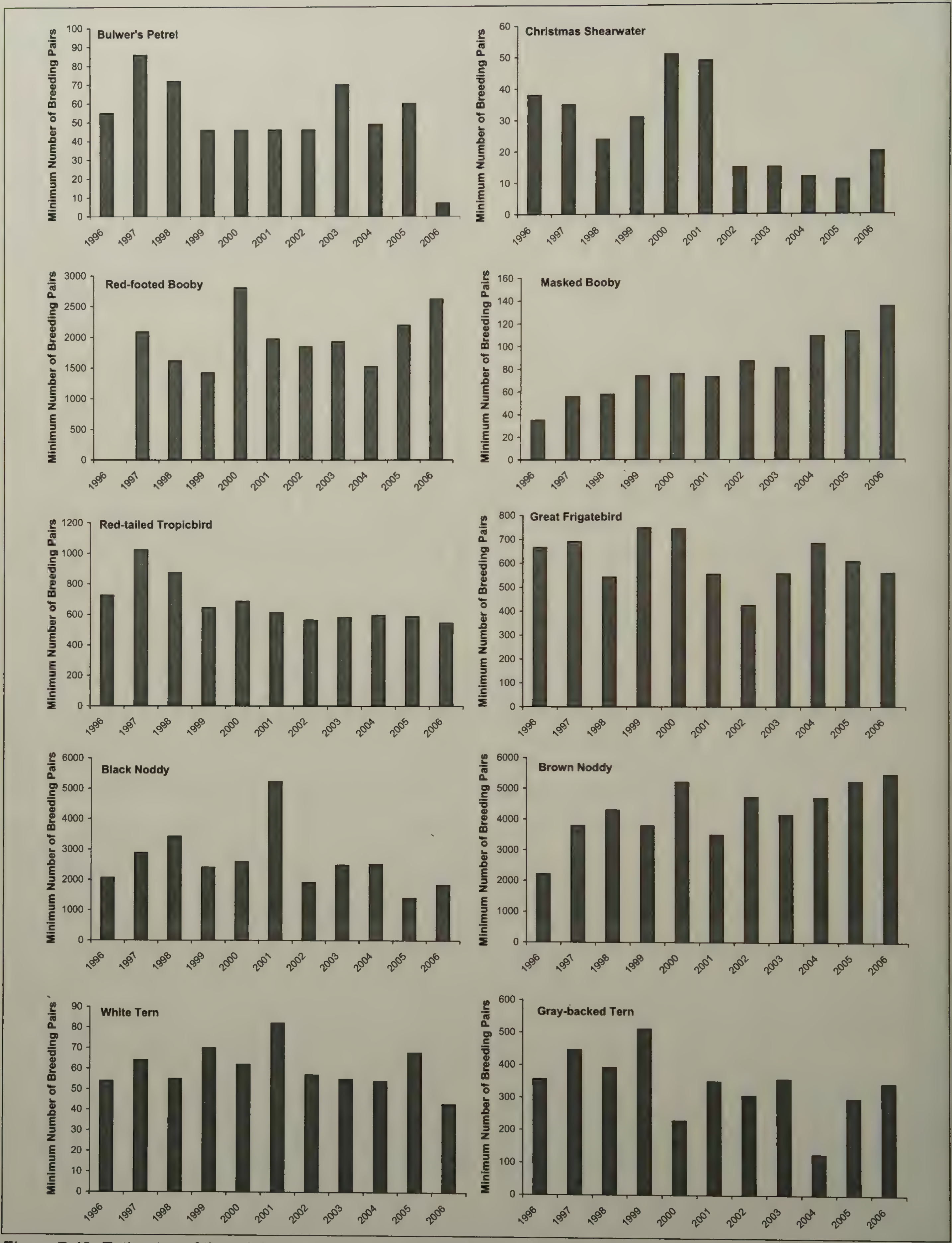


Figure 7.49. Estimates of the minimum numbers of breeding pairs on Tern Island, French Frigate Shoals from 1996-2006. Source: Pacific Seabird Monitoring Database, 2007.

Reproductive Success

Annual nesting success (total number of chicks fledged/total number of eggs laid) from 1996 – 2006 is presented in Figure 7.50 below for Laysan and Black-footed Albatrosses, Bulwer's Petrels, Red-footed Boobies, Masked Boobies, Red-tailed Tropicbirds, Black Noddies, and Gray-backed Terns. Black-footed Albatross reproductive success has remained relatively stable – between approximately 70-80% - over the 11-year period, while Laysan Albatross success has been lower and more variable – between 30% and just over 70% - during the same time period. Reproductive success for Red-tailed Tropicbirds and Gray-backed Terns appears to have declined substantially after the 1996 and 1997 breeding seasons, while all other species' nesting success fluctuated annually over that time period. Cause of the extremely low reproductive success for Black Noddies in 2002 is unknown, although for all species, overall nesting success is tied very closely to food availability in any given year (2002-2003 was an El Niño year, such that food availability may have been low for some seabird species during that time).

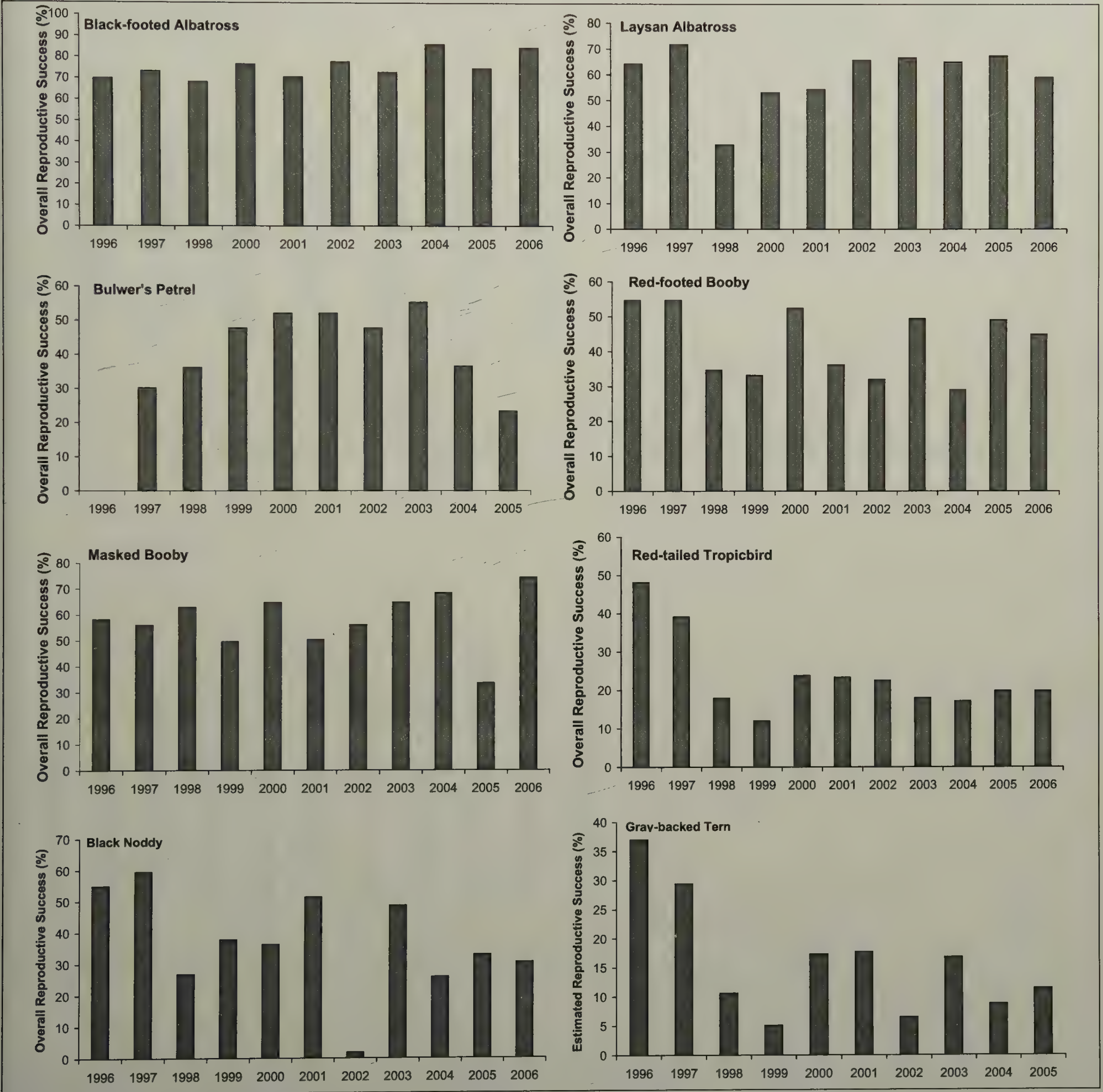


Figure 7.50. Annual nesting success (total number of chicks fledged/total number of eggs laid) from 1996 – 2006. Source: Pacific Seabird Monitoring Database, 2007.

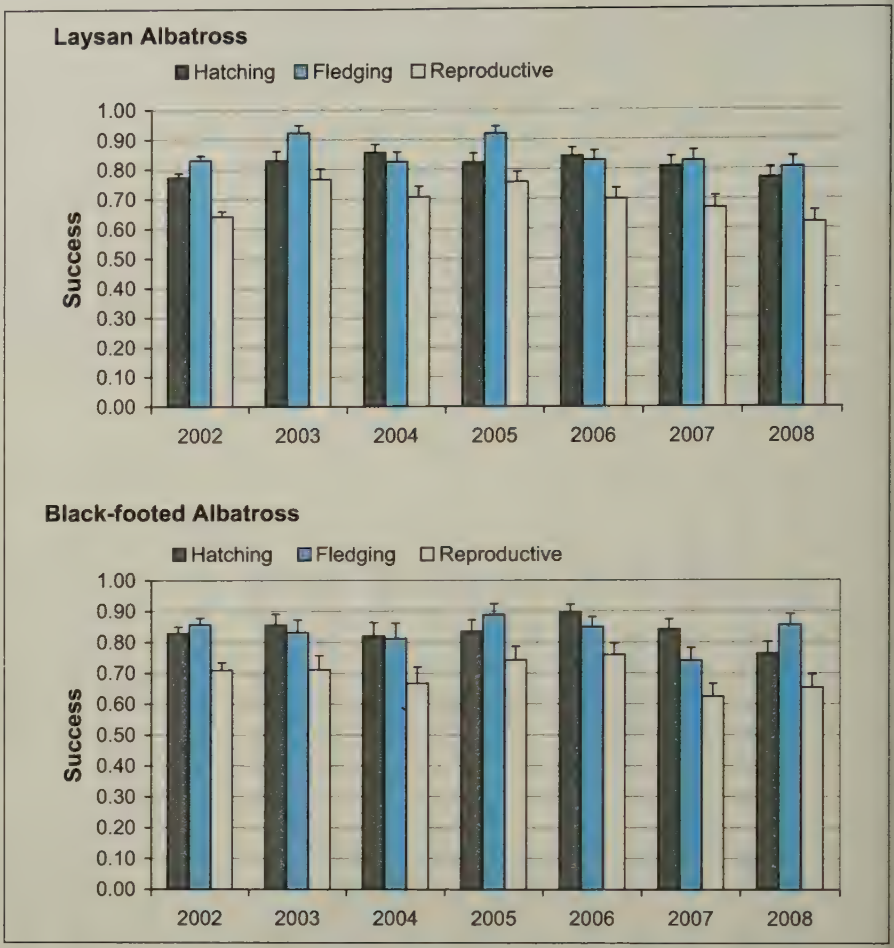
USFWS Monitoring at Midway Atoll

Methods

Laysan and Black-footed Albatross nests have been counted at Midway Atoll since 1991, and beginning in 1997, reproductive success of both species has been monitored. Hatching success, fledging success, and overall reproductive success, have been estimated for both species from 2002 – 2008 (Klavitter et al., 2009). Red-tailed Tropicbird population parameters have also been studied at Midway Atoll since 1997, including reproductive success, adult survival, and overall population trends (Laniawe and Klavitter, 2009; Laniawe, 2008). Seabird monitoring at Midway also currently includes population monitoring of Short-tailed Albatrosses, Brown Boobies, Masked Boobies, Bulwer's Petrels, Tristram's Storm-petrels, Least Terns and Little Terns (J. Klavitter, pers. comm.).

Results

Results of Laysan and Black-footed Albatross nest monitoring from 2002-2008 are presented in Figure 7.51. For this seven-year period, mean Laysan Albatross hatching success was 82% and fledging success was 85%, leading to an overall reproductive success of 69%. Black-footed Albatrosses had similar population paramaters, with a hatching success of 83%, fledging success of 83%, and overall reproductive success of 70% for the entire time period, In analyzing reproductive parameters between species and years, Black-footed Albatrosses had a slightly higher hatching success than Laysan Albatrosses, but the two species had similar fledging and overall reproductive success rates (Klavitter et al., 2009).


Laysan Albatross

Black-footed Albatross

Figure 7.51. The top panel shows Laysan Albatross hatching, fledging, and overall reproductive success at Midway Atoll from 2002-2008.The bottom panel Black-footed Albatross hatching, fledging, and overall reproductive success at Midway Atoll from 2002-2008. Source: Klavitter et al., 2009.

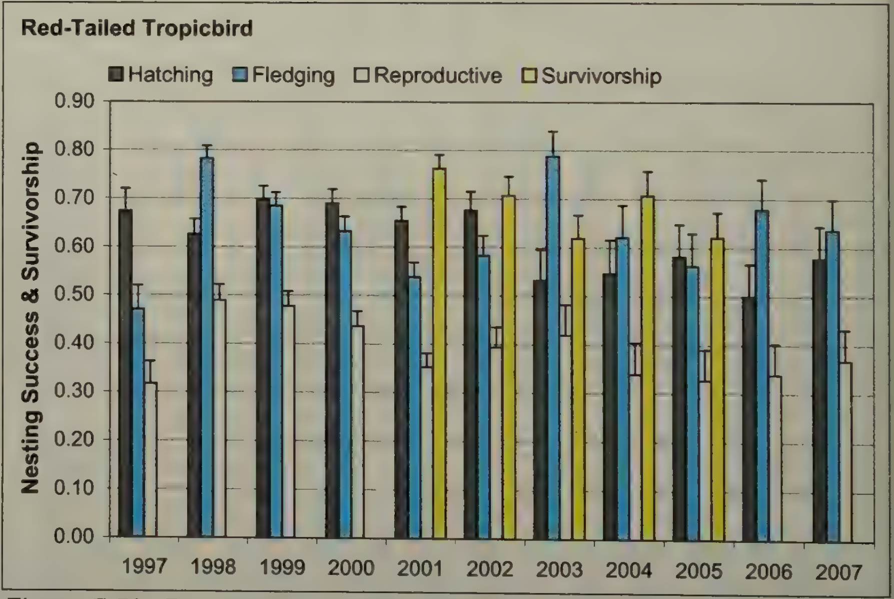

Red-Tailed Tropicbird

Figure 7.52. Red-tailed Tropicbird reproductive success and survival estimates for Midway Atoll from 1997-2007. Source: Laniawe and Klavitter, 2009.

The results of Red-tailed Tropicbird population monitoring at Midway Atoll from 1997-2007 are presented in Figure 7.52. Hatching, fledging, and overall reproductive success, as well as adult survival, varied between years, but for the entire 11-year period, reproductive success was 41%, and adult survival was 70%. These reproductive and survival rates led to an overall population trend of 0.82 for this time period, indicating that the Red-tailed Tropicbird population at Midway Atoll was declining during this time (Laniawe and Klavitter, 2009; Laniawe, 2008).

EXISTING DATA GAPS

Spatial Distribution

Limiting the population monitoring data to three of the islands/atolls within the NWHI reduces our ability to analyze population productivity, survival and community composition across the archipelago. The remoteness, year-around breeding, and underground nesting habits of some of the petrel species make breeding seabird surveys at all of the islands within the Monument logistically difficult. Nest density calculations at the various islands, along with information regarding available habitat (and the extent covered by introduced plants), might allow for analysis and predictions of future impacts from changing sea levels and vegetation change over time. In addition, standardized methods for monitoring reproductive success and survival at French Frigate Shoals, Laysan and Midway Atoll would allow for more comprehensive geographic comparisons of seabirds nesting within the Monument. The collection of at sea seabird survey data should be conducted on a regular basis in order to gain a better understanding of the at sea behavior and environmental conditions for foraging. Currently a single survey was conducted by the NOAA Pacific Southwest Fisheries Science Center in 2002. This type of survey needs to be conducted again and at different times of year in order to gain a better understanding of all the seabirds in the NWHI throughout the year.

REFERENCES

Amerson, A.B. Jr. 1971. The natural history of French Frigate Shoals, Northwestern Hawaiian Islands. Atoll Research Bulletin 150.

Anderson, D.J. 1993. Masked Booby (*Sula dactylatra*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/073

Awkerman, J.A., D.J. Anderson, and G.C. Whittow. 2008. Black-footed Albatross (*Phoebastria nigripes*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/065

Brooke, M. 2004. Albatrosses And Petrels Across The World: Procellariidae. Oxford University Press, Oxford, UK

Chardine, J.W. and R.D. Morris. 1996. Brown Noddy (*Anous stolidus*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/220

Dearborn, D.C. and A.D. Anders. 1996. Reproductive success of Black Noddies, Red-footed Boobies, and Red-tailed Tropicbirds on Tern Island, French Frigate Shoals in 1995. U.S. Fish and Wildlife Service Report, Honolulu, Hawaii, USA.

Dearborn, D.C. and A.D. Anders. 2000. Occurrence and breeding behavior of Lesser Frigatebirds (*Fregata ariel*) on Tern Island, Northwestern Hawaiian Islands. Pacific Seabirds 27: 2-5.

Dearborn, D.C., A.D. Anders, and E.N. Flint. 2001. Trends in reproductive success of Hawaiian seabirds: is guild membership a good criterion for choosing indicator species? Biological Conservation 101: 97-103.

Dearborn, D.C., A.D. Anders, E.A. Schreiber, R.M.M. Adams, and U.G. Mueller. 2003. Inter-island movements and population differentiation in a pelagic seabird. Molecular Ecology 12:2835-2843.

Ely, C.A. and R.B. Clapp. 1973. The natural history of Laysan Island, Northwestern Hawaiian Islands. Atoll Research Bulletin 171.

Fefer, S.I, C.S. Harrision, M.B. Naughton, and R.J. Shallengerger. 1984. Synopsis of results of recent seabird research conducted in the Northwestern Hawaiian Islands. In R.W. Grigg and K.Y. Tanoue, editors. Proceedings of the Second Symposium on Resource Investigations in the Northwestern Hawaiian Islands Vol 1.

Fernandez, P., D.J. Anderson, P.R. Sievert, and K.P. Huyvaert. 2001. Foraging destinations of three low-latitude Albatross (*Phoebastria*) species. J. Zool. London 254: 391-404.

Fisher, H.I. 1976. Some dynamics of a breeding colony of Laysan albatrosses. Wilson Bulletin 88: 121-142.

Gauger, V.H. 1999. Black Noddy (*Anous minutus*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/412.

Gauger Metz, V. and E. A. Schreiber. 2002. Great Frigatebird (*Fregata minor*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/681

Grigg, R.W. and K.Y. Tanoue, editors. 1984. Proceedings of the second symposium on resource investigations in the Northwestern Hawaiian Islands. Sea Grant Miscellaneous Report UNIHI-SEAGRANT-MR-84-01.

Harrison, C.S. 1990. Seabirds of Hawaii: Natural History and Conservation. Cornell University Press, Ithaca, New York.

Harrison, C.S., T.S. Hida, and M.P. Seki. 1983. Hawaiian seabird feeding ecology. Wildlife Monographs 85: 3-71.

Harrison, P. 1987. A Field Guide to Seabirds of the World. The Stephen Greene Press, Lexington, Massachusetts.

Hyrenbach, K.D., P. Fernandez and D.J. Anderson. 2002. Oceanographic habitats of two sympatric North Pacific albatrosses during the breeding season. Marine Ecology-Progress Series 233: 283-301

Hyrenbach, K.D., Keiper, C., Allen, S.G., Ainley, D.G., and D.J. Anderson. 2006. Use of marine sanctuaries by far-ranging predators: commuting flights to the California Current System by breeding Hawaiian albatrosses. Fisheries Oceanography 15: 95-103.

Kappes, M.A., S.A. Shaffer, Y. Tremblay, D.G. Foley, D.M. Palacios, P.W. Robinson, S.J. Bograd and D.P. Costa. (in review). Hawaiian albatrosses track interannual variability of marine habitats in the North Pacific. Progress in Oceanography.

King, W.B. (editor). 1974. Pelagic Studies of Seabirds in the Central and Eastern Pacific Ocean. Smithsonian Contributions to Zoology Number 158.

Klavitter, J., Schubert, G., Laniawe, L., and M. Romano. 2009. Reproductive success of Laysan and black-footed albatrosses from 2002 – 2008 at Midway Atoll National Wildlife Refuge. Pacific Seabird Group Annual Meeting. 18 - 26 February, 2009. Hakodate, Hakkaido, Japan.

Kurata, Y. 1978. Breeding record of the Laysan Albatross *Diomedea immutabilis* on the Ogasawara Islands, Japan. Journal of the Yamashina Institute for Ornithology 10: 185-189.

Laniawe, L. 2008. Survivorship, Productivity, and Foraging Range of the Red-tailed Tropicbird (Phaethon rubricauda) at Midway Atoll National Wildlife Refuge. Thesis. University of East Anglia, Norwich, England, UK.

Laniawe, L. and J. Klavitter. 2009. Reproductive success, survivorship, and population trend of the red-tailed tropicbird 1997 - 2007 at Midway Atoll National Wildlife Refuge. Pacific Seabird Group Annual Meeting. 18 - 26 February, 2009. Hakodate, Hakkaido, Japan.

Lee, D.S. and M. Walsh-Mcgehee. 1998. White-tailed Tropicbird (*Phaethon lepturus*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/353.

Lewison, R. and L.B. Crowder. 2003. Estimating fishery bycatch and effects on a vulnerable seabird population. Ecological Applications 13 (3): 743-753.

Lindsey, T.R. 1986. The seabirds of Australia. Angus and Robertson, Australia.

Megysi, J.L. and D.L. O'Daniel. 1997. Bulwer's Petrel (*Bulweria bulwerii*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/281.

Mostello, C.S., N.A. Palaia and R.B. Clapp. 2000. Gray-backed Tern (*Sterna lunata*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/525.

Niethammer, K.R. and L.B. Patrick. 1998. White Tern (*Gygis alba*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/371.

Pacific Seabird Group and USGS, Alaska Biological Science Center, 2007 Pacific Seabird Monitroing Database. http://www.absc.usgs.gov/research/psinfonet/psmdb/splashpsmdb.htm

Rice, D. W. and K. W. Kenyon. 1962. Breeding distribution, history and populations of North Pacific Albatrosses. Auk 79: 365–386.

Schreiber, E.A., C.J. Feare, B.A. Harrington, B.G. Murray, Jr., W.B. Robertson, Jr., M.J. Robertson and G.E. Woolfenden. 2002. Sooty Tern (*Sterna fuscata*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/665

Schreiber, E.A. and R.L. Norton. 2002. Brown Booby (*Sula leucogaster*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/649

Schreiber, E.A. and R.W. Schreiber. 1993. Red-tailed Tropicbird (*Phaethon rubricauda*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/043

Schreiber, E.A., R.W. Schreiber and G.A. Schenk. 1996. Red-footed Booby (*Sula sula*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/241

Seto, N.W. 2001. Christmas Shearwater (*Puffinus nativitatis*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/561

Seto, N.W. and D. O'Daniel. 1999. Bonin Petrel (*Pterodroma hypoleuca*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/385

Shaffer, S.A., D.M. Palacios, Y. Tremblay, M.A. Kappes, D.G. Foley, S.J. Bograd, and D.P. Costa. (in review). A tale of two hotspots. Segregation at sea by post-breeding Hawaiian albatrosses. Journal of Animal Ecology.

Shaffer, S.A., Y. Tremblay, J.A. Awkerman, R.W. Henry, S.L.H. Teo, D.J. Anderson, D.A. Croll, B.A. Block and D.P. Costa. 2005. Comparison of light- and SST-based geolocation with satellite telemetry in free-ranging albatrosses. Marine Biology 147: 833-843

Slotterback, J. W. 2002. Tristram's Storm-petrel (*Oceanodroma tristrami*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/673b

Suryan, R.M., D.J. Anderson, S.A. Shaffer, D.D. Roby, Y. Tremblay, D.P. Costa, P.M. Sievert, F. Sato, K. Ozaki, G.R. Balogh and N. Nakamura.(in press) Wind, waves, and wing-loading: Specialization in two Pacific albatross species. PLoS One.

Suryan, R.M., F. Sato, G.R. Balogh, K.D. Hyrenbach, P.R. Sievert, and K. Ozaki. 2006. Foraging destinations and marine habitat use of short-tailed albatrosses: A multi-scale approach using first-passage time analysis. Deep-Sea Research Part Ii-Topical Studies in Oceanography 53: 370-386.

U.S. Fish and Wildlife Service. 2005. Seabird Conservation Plan Pacific Region.

U.S. Fish and Wildife Service. 2008. Biological program standard operating procedures (SOPs): French Frigate Shoals, Hawaiian Islands National Wildlife Refuge. U.S. Fish and Wildlife Service, Honolulu, Hawaii, USA.

Weimerskirch, H., Le Corre, M., Jaquemet, S., Potier, M., and R. Marsac. 2004. Foraging strategy of a top predator in tropical waters: great frigatebirds in the Mozambique Channel. Marine Ecology Progress Series 275: 297-308.

Whittow, G.C. 1993. Laysan Albatross (*Phoebastria immutabilis*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/066

Whittow, G.C. 1997. Wedge-tailed Shearwater (*Puffinus pacificus*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/305

PERSONAL CONTACTS

Anders, A. Clancy Environmental Consultants. Honolulu, HI, USA.

Flint, B. U.S. Fish and Wildlife Service, Honolulu, HI, USA.

Klavitter, J. USFWS, Honolulu, HI, USA.

WEBSITES

Hawaii Division of Forestry and Wildlife. 2008. http://www.state.hi.us/dlnr/dofaw/cwcs/Conservation_need.htm#Species

Pacific Seabird Group and USGS, Alaska Biological Science Center, 2007 Pacific Seabird Monitroing Database. http://www.absc.usgs.gov/research/psinfonet/psmdb/splashpsmdb.htm

Nonindigenous and Invasive Species

Kevin See[1], Scott Godwin[2] and Charles Menza[3]

INTRODUCTION

The Northwestern Hawaiian Islands (NWHI) represents a relatively pristine marine ecosystem with few nonindigenous and invasive species. Of the 343 nonindigenous species (NIS) found in the water's of the Main Hawaiian Islands (MHI), only 13 have been detected in the NWHI (Eldredge and Carlton, 2002; Godwin et al., 2006; Godwin et al., 2008). This difference is likely due to the NWHI's extreme remoteness, relatively low rates of visitation and concerted management efforts. Still, the threat of nonindigenous species spreading from the MHI to the NWHI and becoming invasive is a serious concern. The terms nonindigenous and invasive are both used to refer to species that are living outside of their historic native range. The difference is that invasive species have been shown to cause environmental or economic harm, while NIS have not. Most NIS currently found in the NWHI are in few locations and in low abundances. There is debate as to whether any are invasive, but this is an active area of research (Schumacher and Parrish, 2005).

A total of 13 nonindigenous species have been authoritatively detected in the NWHI (Figure 8.1; Table 8.1). These species range from invertebrates to fish, and have a wide variety of life histories, likely modes of introduction and potential impacts. Some species have been found in only one or two locations (e.g., the red alga *Hypnea musciformis*), whereas others are widely distributed throughout most of the atolls and shoals (e.g., the blueline snapper *Lutjanus kasmira*). The difference in their distributions is related to their movement speeds, transport methods, ecological success and probability of detection.

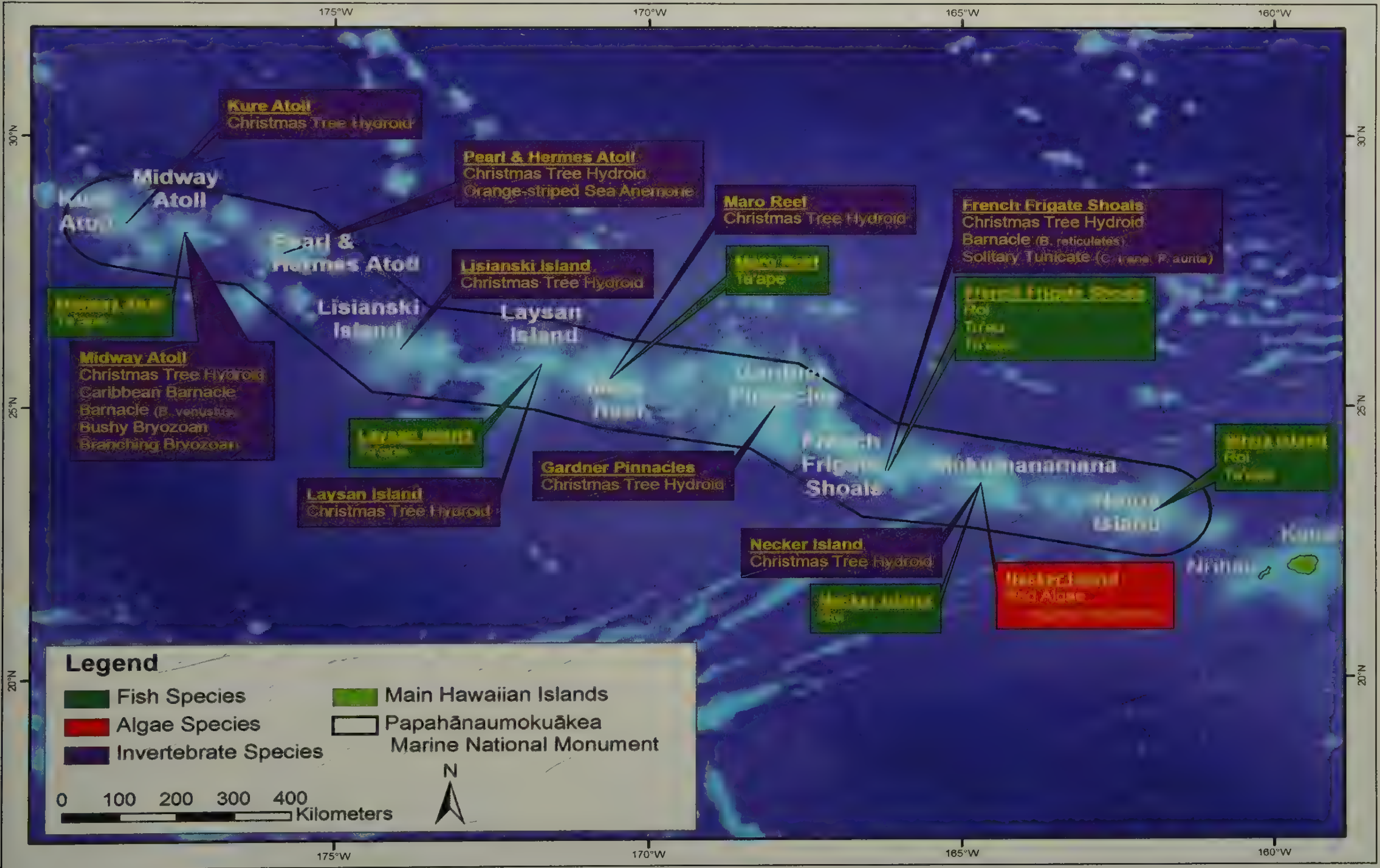


Figure 8.1. Documented distribution of nonindigenous and invasive species in the NWHI. Map: K. Keller.

---

1. University of Washington
2. University of Hawaii
3. NOAA/NOS/NCCOS/CCMA Biogeography Branch

Table 8.1. Marine nonindigenous and invasive species in the Northwest Hawaiian Islands. The table also includes information on their native range, where they have been seen in the NWHI, present population status and potential impacts. Sources: Abbott, pers comm; DeFelice et al., 1998; DeFelice et al., 2002; Godwin et al., 2004; Godwin, 2008; Godwin, pers comm; Waddell et al., 2008; Zabin et al., 2004.

SCIENTIFIC NAME	COMMON NAME	TAXA	NATIVE RANGE	PRESENT STATUS	SIGHTINGS	POTENTIAL IMPACT
Hypnea musciformis	Red alga	Algae	Unknown; Cosmopolitan	Unknown; in drift and on lobster traps	MMM	Change community structure and diversity of benthic habitat, including overgrowing coral. Currently forms large blooms, up to 7,465 kg (or 20,000 lbs), off the coast of Maui.
Diadumene lineata	Orange-striped sea anemone	Anemone	Japan	Unknown; on derelict net only	PHR	Fouling organism. Ecological impact is unstudied but presumed minimal.
Pennaria disticha	Christmas tree hydroid	Hydroid	Unknown; Cosmopolitan	Established	MMM, FFS, GAR, MAR, LAY, LIS, PHR, MID, KUR	Competition for space with other invertebrates. Also stings humans, causing a mild irritation.
Amathia distans	Bushy bryozoan	Bryozoan	Caribbean	Established	MID	Fouling organism. Ecological impact is unstudied but if it becomes established in protected coastal areas it has the potential to overgrow coral reefs.
Schizoporella errata	Branching bryozoan	Bryozoan	Mediterranean	Established	MID	Fouling organism. Ecological impact unstudied, but observations suggest some competition for space with other fouling invertebrates.
Balanus reticulatus	Barnacle	Barnacle	Atlantic	Established on seawall	FFS	Fouling organism. Ecological impact is unstudied but presumed minimal.
Balanus venustus	Barnacle	Barnacle	Atlantic and Caribbean	Not established; on vessel hull only	MID	Fouling organism. Ecological impact is unstudied but presumed minimal.
Chthamalus proteus	Caribbean barnacle	Barnacle	Caribbean	Established in harbor	MID	Serious nuisance fouling organism. Competes for space and food resources with native species. Grows in such densities that it could exclude algal grazers such as opihi.
Cnemidocarpa irene	Styelidae, solitary tunicate	Tunicate	Indo-Pacific	Autonomous Reef Monitoring Structures (ARMS)	FFS	The impacts of this species are unknown but it has the capacity to become a dominant fouling organism on any man-made substrate.
Polycarpa aurita	Styelidae, solitary tunicate	Tunicate	Indo-Pacific, Western Atlantic	ARMS	FFS	This species has the capacity to become an aggressive component of a fouling community on man-made surfaces, and the potential for recruitment to natural habitats is always a possibility.
Lutjanus fulvus	Toau or Blackline Snapper	Fish	Indo-Pacific	Established	FFS	Could out-compete native species for resources, but current densities may be too low to see these effects.
Lutjanus kasmira	Taape or Blueline snapper	Fish	Indo-Pacific	Established	NIH, FFS, MAR, LAY, MID	Could prey on or out-compete desirable fishery species. May also exclude more desirable species from fishing gear through competition. Scientific research into these effects is currently lacking.
Cephalopholis argus	Roi or Peacock grouper	Fish	Indo-Pacific	Established	NIH, MMM, FFS	May predate on native species that are targeted by aquariums, dive tours and fishermen. Scientific research into these effects is currently lacking.
Carijoa riisei	Snowflake coral	Octocoral	Indo-Pacific	Has not been seen in NWHI yet	Five Fathom Pinnacle	Overgrows black corals, killing them. Competes for space with other invertebrates.
Acanthophora spicifera	Red alga	Algae	Indo-Pacific	Has not been seen in NWHI yet	Kauai	Change community structure and diversity of benthic habitat, including overgrowing coral.

Island/atoll abbreviations found throughout this chapter: NIH = Nihoa, MMM = Mokumanamana, FFS = French Frigate Shoals, GAR = Gardner Pinnacles, MAR = Maro Reef, LAY = Laysan Island, LIS = Lisianski Island, PHR = Pearl and Hermes Atoll, MID = Midway Atoll, KUR = Kure Atoll

All of the atolls and islands have at least one nonindigenous species, but several such as Midway Atoll (six species) and French Frigate Shoals (five species) have numerous. These two locations have been the foci of human activity for many years, especially during World War II when they were used as military bases. This activity probably meant greater ship traffic and food imports, both of which are considered principal NIS vectors. They are also two of the most studied locations and thus present NIS have a greater probability of detection.

In addition to confirmed NIS observations in the NWHI, several unconfirmed reports of sightings exist and two other species (i.e., *Carijoa riseii* and *Acanthophora Spicifera*) have proven to be extremely successful invaders of the MHI, and therefore pose a serious threat to the NWHI. The red algae *Hypnea musciformis* and *Acanthophora spicifera* may have been sighted drifting on Maro Reef and sighted near Midway Atoll, respectively. The blackline snapper (*Lutjanus fulvus*) may have been spotted off Nihoa Island, and blueline snapper (*L. kasmira*) may have been seen off Mokumanamana, Lisianski Island, and Pearl and Hermes Atoll (Godwin et al., 2006, Draft Environmental Impact Statement, Draft Management Plan for the NWHI Proposed National Marine Sanctuary 2006, R. Kosaki, pers. comm.).

Vectors

Populations of nonindigenous marine species that have already colonized areas of the MHI represent the most likely source of nonindigenous species in the NWHI. This deduction is based on the proximity and pattern of ship movements among these two areas (Godwin et al., 2006). It is difficult to conclusively determine vectors of movement, but the most likely are: hull fouling, ballast water discharge and natural water currents. Recently, marine debris has been suggested as a vector and has shown the ability to transport nonindigenous species to the NWHI (Godwin et al., 2006). To date no records show any species were purposefully introduced into the NWHI, although they most certainly were to the MHI (e.g., blueline and blackline snapper, Peacock grouper).

Data Collection

To deal with the threat of NIS and invasive species, information about their biology and spatial distribution is critical. Sightings of marine invasive species in the NWHI come from a variety of sources (Table 8.2). Sources are typically biological inventories of particular areas (e.g., Midway Harbor Survey, French Frigate Shoals Survey) or are opportunistic (e.g., derelict fishing net removal project) and thus are limited in temporal and spatial scope. These types of data are useful for determining if a particular location has been invaded, or if a potential vector is acting as an invasive pathway. However, these data do not provide any indication of the severity of an invasion, whether an invasive population is growing or shrinking or the ability to complete a rigorous statistical comparison among locations.

Currently, there is no systematic survey which covers all habitats likely to harbor NIS and invasive species. Most data are collected or informed by conventional SCUBA or snorkeling. As a result, most data are collected at depths shallower than 35 m. This is a concern since several nonindigenous species already detected in the NWHI or in the MHI have been detected well below this limit (e.g., blueline snapper – 256 m). To fill this gap Papahanaumokuakea Marine National Monument (PMNM) has begun assessing deep water survey technologies (C. Menza, pers. comm.).

The NWHI Coral Reef Assessment and Monitoring Program (NOWRAMP) and lobster trap monitoring programs provide quantitative abundance data of NIS and can monitor changes over time (see Table 8.2 for details); however sampling is spatially biased. For example, NOWRAMP surveys are completed at permanent sites and thus may not be representative of larger populations and may not detect NIS that occur in unsampled habitats. Similarly, hull, net and trap inspections are tied to the distribution of invasive species and may provide biased population estimates of attached species. More intensive surveys in specific areas (e.g., Midway Harbor Survey) offer detailed fine spatial scale data and taxonomic resolution, but are time intensive and costly.

Table 8.2. Marine invasive species monitoring programs in the NWHI.

PROGRAM	OBJECTIVES	TIME PERIOD	ISLANDS OR ATOLLS	AGENCIES
NOWRAMP	Monitor fish, algae, coral and other invertebrates	2000-2007	NIH, MMM, FFS, GAR, MAR, LAY, LIS, PHR, MID, KUR	NOAA-PMNM, PIFSC
Midway Harbor Survey	Survey the invertebrates on artificial substrates in and around Midway Harbor	1998	MID	USFWS, Bishop Museum
French Frigate Shoals Survey	Survey the seawall at Tern Island for nonindigenous species	2002	FFS	USFWS, Bishop Museum
Derelict Fishing Net Removal Project	Remove derelict fishing nets on Kure, Pearl and Hermes, Midway and Lisianski and determine if any nets contained nonindigenous species	2000	LIS, PHR, MID, KUR	NOAA-NMFS
Derelict Fishing Net Removal Project	Remove derelict fishing nets on French Frigate Shoals and determine if any nets contained nonindigenous species	2007	FFS	NOAA-NMFS
Census of Coral Reefs	Characterize invertebrate communities	2007	FFS	NOAA-NMFS
Hull Fouling Project	Assess hull fouling as a mechanism for the dispersal of nonindigenous species	2003	MHI, MID	HCRI-RP, HI-DLNR
Lobster Trap Monitoring	Monitor the population of spiny lobsters, and identify any algae that is growing on the lobster traps	1985-2007	MMM, MAR	NOAA-PIFSC

Abbreviations: NOWRAMP = Northwest Hawaiian Islands Rapid Assessment and Monitoring Program, MHI = Main Hawaiian Islands, NOAA = National Oceanic and Atmospheric Administration, PMNM = Papahanaumokuakea Marine National Monument, USFWS = U.S. Fish and Wildlife Service, NMFS = National Marine Fisheries Service, HI DLNR = Hawaii Department of Land and Natural Resources, PIFSC = Pacific Islands Fisheries Science Center, HCRI-RP = Hawaii Coral Reef Initiative Research Program

MARINE ALGAE

Nonindigenous algae in the NWHI are a major concern, because of the mobility of propagules, fast growth rate, potential ecological impacts to the native benthic community and presence in the MHI. One species of red algae, *Hypnea musciformis*, has been detected in the NWHI and another species, *Acanthophora spicifera*, is of particular concern because of its aggressive growth rate. Both species are present in the MHI and *H. musciformis* probably originated there.

At least 19 species of macroalgae have been intentionally or passively introduced in Hawaii since the mid 1950s (Doty, 1961; Brostoff, 1989; Rodgers and Cox, 1999; Russell, 1987, 1992; Woo, 1999; Smith et al., 2002; Smith et al., in press) and at least five have successfully established themselves. These species are capable of moving to the NWHI.

Red Algae, Spiny Algae (*Acanthophora spicifera*)

This species of red algae has not yet been authoritatively recorded in the NWHI, but there has been one unconfirmed sighting at Midway and due to its success in the MHI, it is a species of particular concern. It is widely distributed among the MHI and throughout the tropics and subtropics. Introduction likely originated in Honolulu Harbor in the 1950s via a fouled barge originating in Guam (Doty, 1961). It has since spread to all the MHI, and is the most widespread invasive algae in the archipelago and is now a common component of the intertidal community (Smith et al., 2002).

Movement and associated range extensions occur naturally through water movement, or anthropogenically through hull fouling. Fragments or spores move through advection and are likely the means of local dispersal in Hawaii (Kilar and McLachlan, 1986). Branches are brittle that often results in fragmentation. Fragments can accumulate forming large, free-floating populations and can drift for potentially long distances before settling and establishing new colonies. It is also frequently spotted fouling hulls throughout the MHI (Smith et al., 2002).

A. spicifera can adapt to a variety of habitats and environmental conditions, and this is one of the reasons of its success throughout tropical and subtropical ecosystems. In Hawaii, it is abundant in protected areas where it is not exposed to high-energy wave action, such as rocky intertidal beaches, tide-pools and shallow reef-flats. It attaches to hard substrates and is often found growing with the native algae species of *Laurencia nidifica* and *Hypnea cervicornis* (Botany UH, 2001). In other areas it has been found as an epiphyte on other algae species and as a free living drift alga.

Potential impacts are poorly studied. It likely impacts the community structure and diversity of the benthic habitat through competition and smothering (Preskitt, 2002; Eldrege 2003), but these effects have not been well quantified (Shluker, 2003). *A. spicifera* can outcompete native algae such as *L. nidifica* and *H. cervicornis* (Russell, 1992). In the eastern tropical Pacific, blooms of *A. spicifera* covered by cyanobacterial epiphytes have been observed at several reefs and were associated with widespread coral mortality.

Red Algae (*Hypnea musciformis*)

In 2005, international press coverage drew attention to the potential spread of the red, invasive alga, *Hypnea musciformis* when large quantities were found entangled in lobster traps at depths from 30 to 90 m near Mokumanamana (Godwin et al., 2006; Figure 8.2). The species was first recorded from deep water (>30 m) at Mokumanamana in 2002, and one small individual was found as part of a drift assemblage at Maro Reef (Friedlander et al., 2008). From 2002 through 2004, small sprigs of the alga were commonly recorded on lobster traps at Mokumanamana. In spring to early summer of 2005, pounds of *H. musciformis* began to appear on lobster traps at Mokumanamana, generating concern about a large-scale epidemic of this nuisance alga. Later that year a special cruise was organized by PMNM to investigate the problem. Interestingly, no *H. musciformis* was discovered at Mokumanamana during the cruise, and continued investigations of algae associated with lobster traps in 2006 have failed to find any significant population blooms other than a few small individuals similar to those documented in 2002 through 2004 (Friedlander et al., 2008).

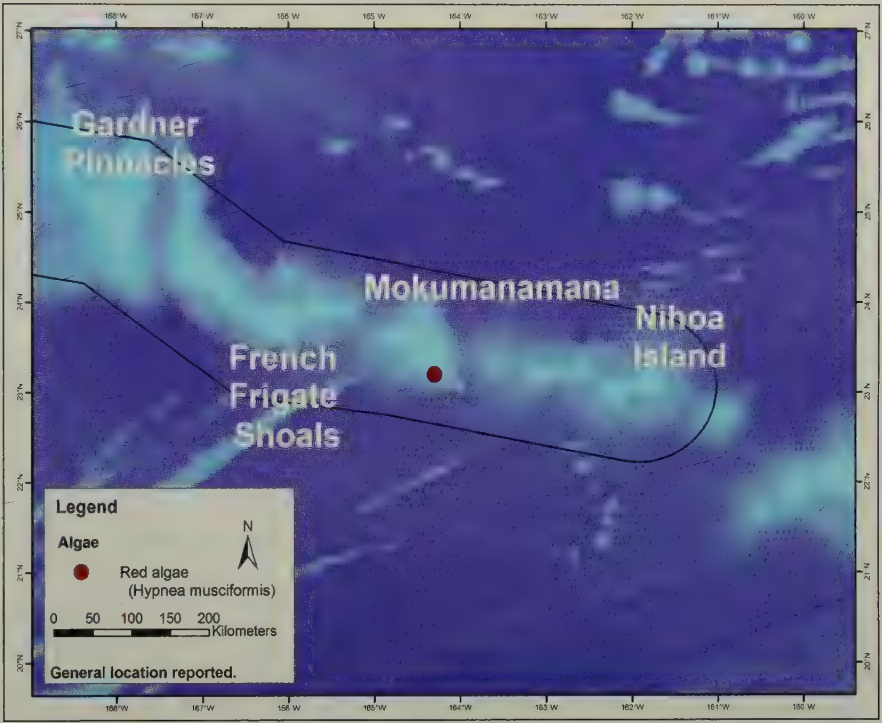

Gardner Pinnacles
Mokumanamana
Nihoa Island
French Frigate Shoals
Legend
Algae
● Red algae (Hypnea musciformis)
N
0 50 100 150 200 Kilometers
General location reported.

Figure 8.2. General location of the red algae Hypnea musciformis *from NOAA/PIFSC lobster trap monitoring.*

H. musciformis was intentionally introduced from its native range in Florida to Kaneohe Bay on Oahu in 1974 for mariculture. It is commercially cultivated as a food source and for kappa carrageenan, a common food additive. Like *A. spicifera*, it spreads quickly and is distributed widely throughout the MHI where it is now found on Kauai, Oahu, Molokai and Maui, with the most abundant populations occurring on Maui (Botany UH, 2001). Populations are often found on calm intertidal and shallow subtidal reef-flats where it either attaches to sandy flat rocks or is found as an epiphyte on other algae species, often on *A. spicifera*, *Laurencia nidifica*, *Sargassum echinocarpum*, and *S. polyphyllum* (http://hawaii.edu/reefalgae/invasive_algae/index.htm).

Principal reasons for this species success are its high growth rate, ability to epiphytize other algae and frequent fragmentation. Russell (1992) estimated a growth rate between 10-50% per day. Drifting fragments can attach to other floating algae, like *S. echinocarpum* or *S. polyphyllum*, and float long distances before establishing new colonies. Attachment is aided by the presence of apical hooks (Figure 8.3). Fragments as small as 5 mm proved viable, growing at a rate of 200% a week (Smith et al., 2002). Besides fragmentation, *H. musciformis* also spreads through hull fouling.

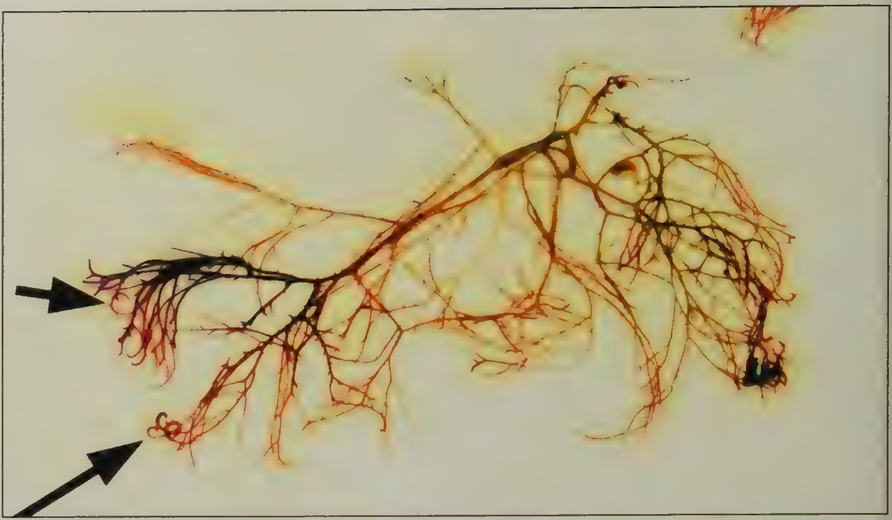


Figure 8.3. H. musciformis. *The arrows point to the species' distinctive hooks. Photo: P. Vroom.*

Potential impacts include competition with native algae and the creation of large dense surface mats. Like other invasive algae, it probably impacts the community structure and diversity of the benthic habitat, but these effects have not yet been quantified (Shluker, 2003). Russell (1992) found *H. musciformis* can outcompete the native algae *H. cervicornis*, especially in the presence of *A. spicifera. H. musciformis* can form large dense mats, which have been correlated with high levels of nutrient inputs from the coast. Similar nutrient inputs are not present in the NWHI, but mats located around the MHI are capable of supplying propagules for distribution to the NWHI. The presence of dense mats are also a concern, because in peak blooms tens of thousands of pounds of algae can wash ashore forming windrows 0.5 m high. The effect of these windrows on local biota like the Hawaiian monk seal or green sea turtle is unknown.

H. musciformis now makes up a significant portion of the diet for the green sea turtle, sometimes composing as much as 99-100% of the seaweed mass in their stomachs. However, the nutritional value of *H. musciformis* has not yet been determined and so the long-term impact of incorporating this alga into the sea turtles' diet is unknown (Botany UH, 2001).

INVERTEBRATES

Out of the all the different taxonomic groups of NIS, invertebrates represent the most species and are the least studied. Nine invertebrate species (one anemone, one hydroid, two bryozoans, three barnacles and two tunicates) have been detected in the NWHI. These invertebrates are typically cryptic and have been detected with the help of fine-scale surveys in targeted areas (e.g., Defelice et al., 1998, 2002). Most nonindigenous invertebrates have been detected at Midway Atoll and French Frigate Shoals, the two locations with the lion's shares of survey effort and human activity. A tenth invertebrate species, the snowflake coral (*Carijoa riseii)*, which has not been detected in the NWHI is described herein because it is a species of particular concern.

Orange-striped Sea Anemone (*Diadumene lineata)*

The orange-striped sea anemone is native to Japan, but has spread throughout the Pacific, Atlantic, Caribbean, the North Sea and the Mediterranean (Zabin et al., 2004). In 2000, about 100 individuals were identified in the lagoon at Pearl and Hermes Atoll attached to a derelict fishing net (Zabin et al., 2004; Figure 8.4). To date, no established adults have been seen in the NWHI.

Although it can reproduce sexually, it likely spreads through asexual reproduction and hull fouling in the NWHI (Zabin et al., 2004). It exhibits a wide tolerance of temperature and salinity and is generally found on solid substrates, in intertidal pools or protected shallow waters such as bays and harbors. The orange-striped sea anemone is often found with mussels and oysters in other parts of its range (DeFelice et al., 2001), and could have been transported to Hawaii in an oyster shipment (Zabin et al., 2004). The impacts of this species in the NWHI remain unknown and unstudied.

Christmas Tree Hydroid *(Pennaria disticha)*

The Chrismas tree hydroid is native to the western Atlantic and has been reported in all of the NWHI except Nihoa (Godwin et al., 2006). It also is widely distributed among the MHI (DeFelice et al., 2001). It was first reported in the region during a survey of Pearl Harbor in 1929 (DeFelice et al., 2001).

It attaches to natural and artificial hard substrates where there is some water movement. It is very common in harbors in all the MHI and is often found in more protected areas such as cracks and crevices on reefs, at depths of 0–50 m. The impacts of the Christmas tree hydroid are unstudied, but it is likely that it competes for space with other invertebrates. It also can sting humans, resulting in minor irritation (DeFelice et al., 2001).

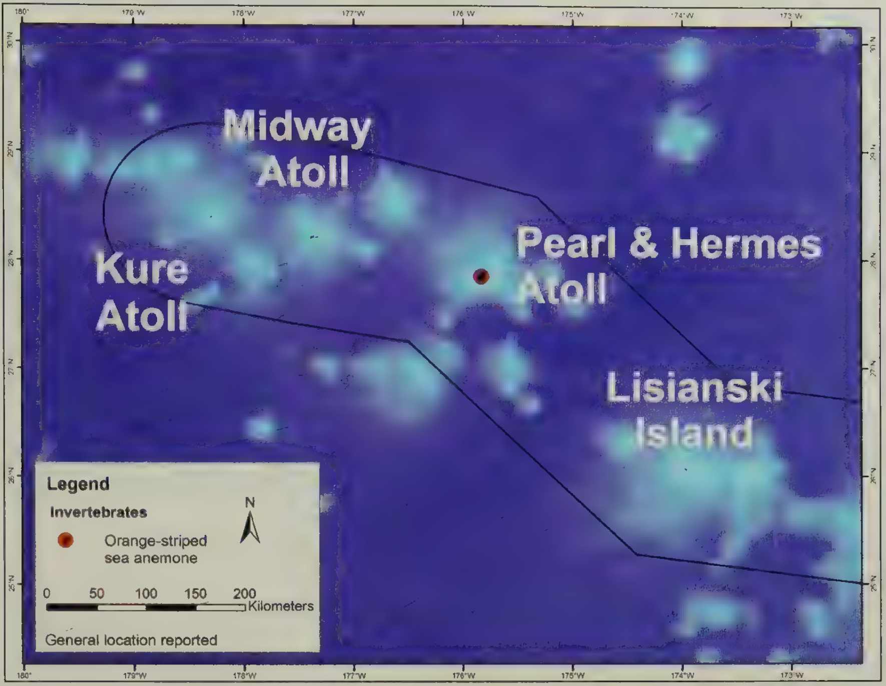

Midway Atoll
Kure Atoll
Pearl & Hermes Atoll
Lisianski Island
Legend
Invertebrates
Orange-striped sea anemone
N
0 50 100 150 200 Kilometers
General location reported

*Figure 8.4. General location of the orange-striped sea anemone (*Diadumene lineata*) from NOAA/PIFSC/CRED Marine Debris Program.*

Bushy Bryozoan (*Amathia distans*)

In 1997 the bushy bryozoan was found at Midway Harbor, dominating many of the manmade structures that were surveyed (Figure 8.5). It formed large colonies on wood, concrete and metal pilings, as it does in harbors in the MHI (DeFelice et al., 1998). To date, this is the only location in the NWHI where it has been sighted. Its native range is the Caribbean, but it has spread over much of the tropics and subtropics including the western Atlantic, Mediterranean and Red Seas, eastern Pacific and coastal waters of Australia, New Zealand, Java and Japan (DeFelice et al., 2001). Movement is considered to be aided by hull fouling, ballast water discharge (larvae) or natural water movement (Shluker, 2003).

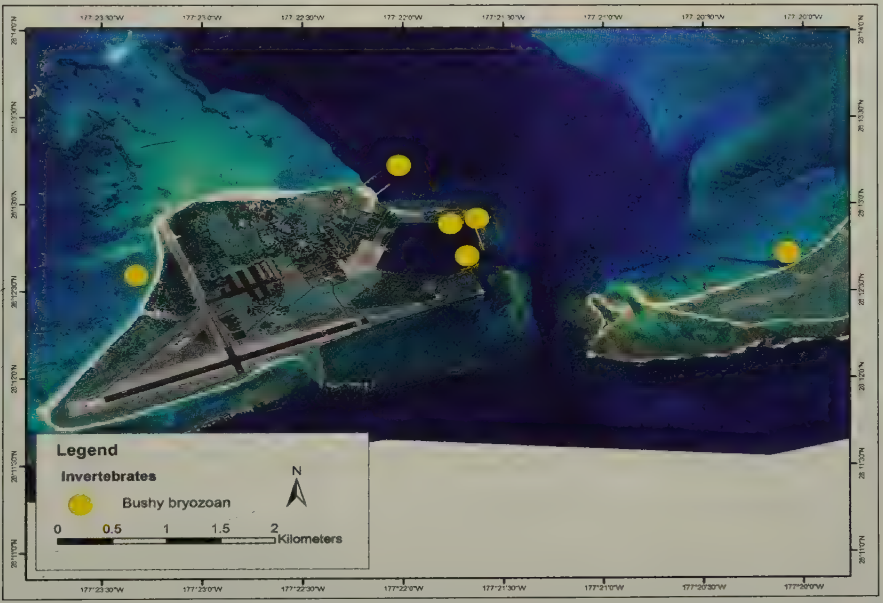


*Figure 8.5. General locations of the bushy bryozoan (*Amathia distans*) at Midway Atoll.*

The bushy bryozoan was first spotted in the region at Kaneohe Bay in 1935, and has since spread to all the MHI (Shluker, 2003; Coles et al., 2004). It can be found in shallow water on hard anthropogenic substrates such as pilings and vessel hulls and natural substrates such as coral rubble. It is usually found inside harbors or embayments, or occasionally in more protected areas of the reef. The impacts of the bushy bryozoan are unknown and presumed minimal (DeFelice et al., 2001), probably including competition for space (Shluker, 2003).

Branching Bryozoan (*Schizoporella errata*)

The branching bryozoan was recorded at Midway Harbor in 1997, where it was found occupying many of the same locations as the bushy brozoan, although not as abundant (DeFelice et al., 1998) (Figure 8.6). It is usually found inside harbors or embayments on man-made substrates, or occasionally in more protected areas of coral reefs (DeFelice et al., 2001). Its native range is the Mediterranean, but is now found worldwide, including all the MHI (DeFelice et al., 2001) where it was first described at Pearl Harbor in 1933. It can be transported anthropogenically through hull fouling, which is likely how it was unintentionally transported to so many locations around the globe (Shluker, 2003). The impacts of this species are unknown, but likely include competition for space (DeFelice et al., 2001).

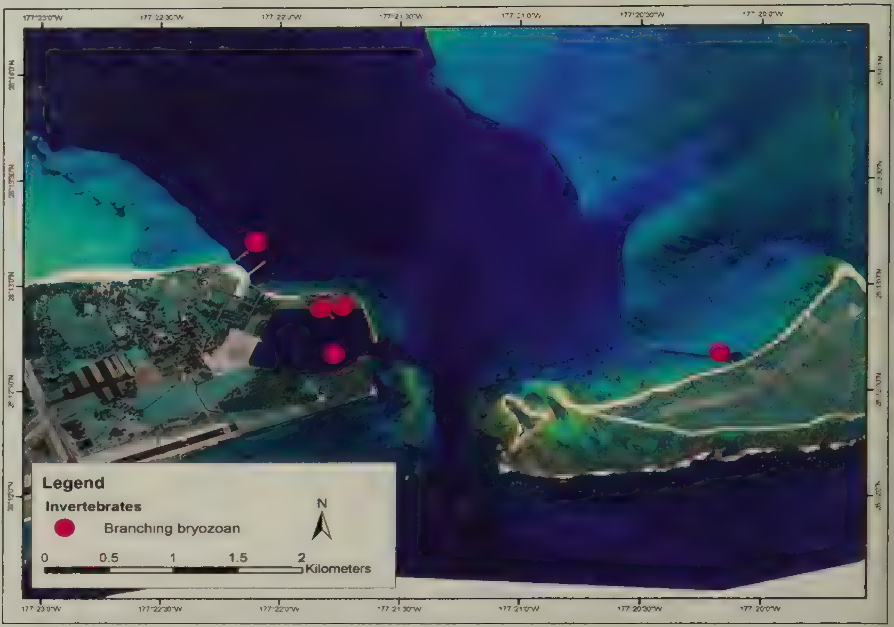


*Figure 8.6. General locations of the branching bryozoan (*Schizoporella errata*) at Midway Atoll.*

Barnacle (*Balanus reticulates*)

Although this species of barnacle has been found in the MHI on Kauai, Oahu, Maui and Hawaii (Coles et al., 2004), and was found on about 25% of the ship hulls in one hull fouling study (Godwin et al., 2004), it has only been spotted once in the NWHI, on a seawall at Tern Island in French Frigate Shoals in 2002 (DeFelice et al., 2002; Figure 8.7). It is a fouling organism. Its ecological impact is presumed to be minimal, although there is little research to confirm this assumption.

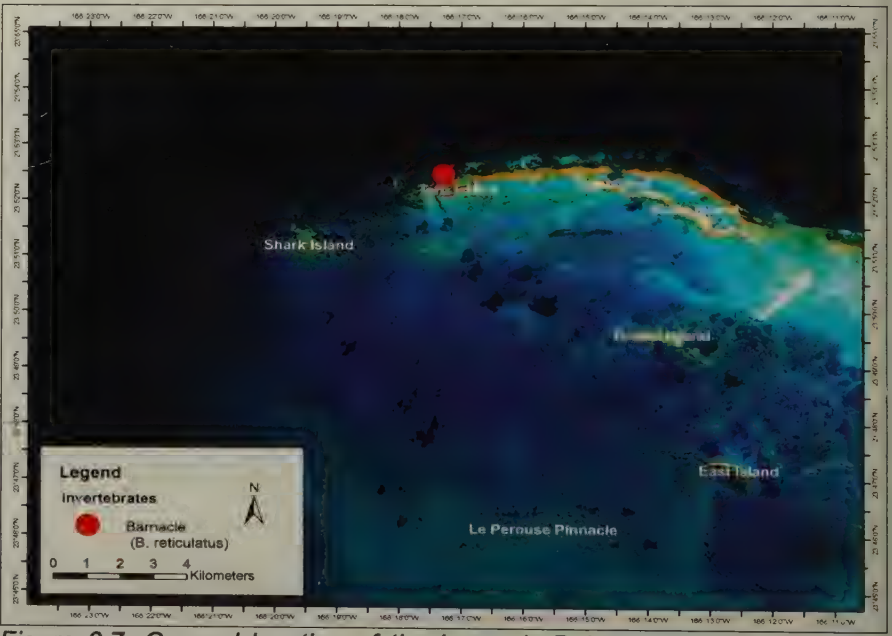


*Figure 8.7. General location of the barnacle *Balanus reticulatus* at Tern Island, French Frigate Shoals.*

Barnacle (*Balanus venustus*)

This barnacle, native to the Atlantic and Caribbean oceans, has been seen once on a hull of a ship anchored at Midway Harbor in 2003 (Godwin et al., 2004), demonstrating this species' ability to be transported through hull fouling. However, an established adult has never been seen in the NWHI. Its ecological impact is presumed to be minimal.

Caribbean Barnacle (*Chthamalus proteus*)

This barnacle from the Caribbean was found in Midway Harbor attached to pier pilings in 1997 (DeFelice et al., 1998; Figure 8.8). It likely arrived in the region between 1973 and 1994, since it was first noticed at Kaneohe Bay, Oahu in 1995 and was not found during a comprehensive intertidal survey of Oahu in 1972.

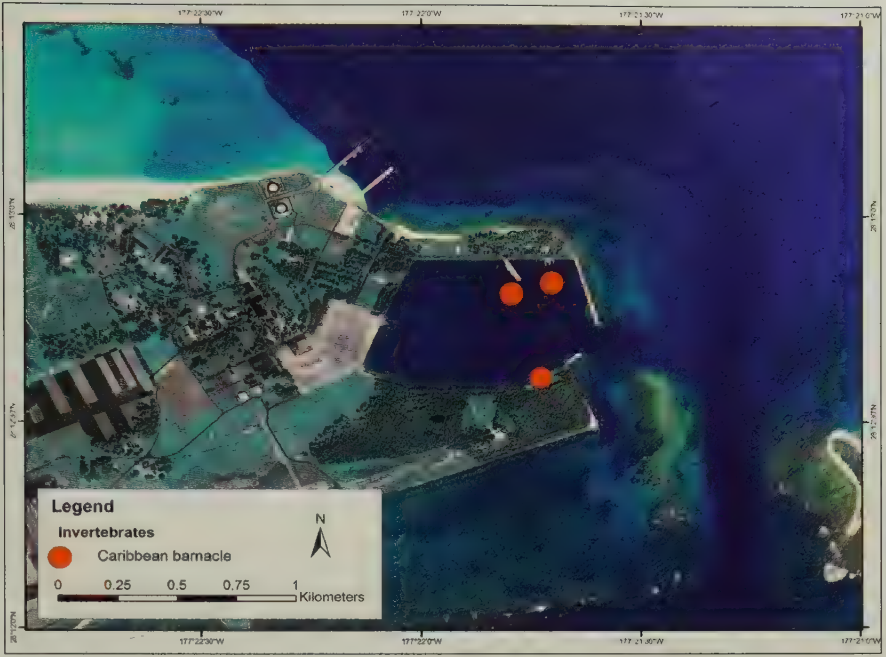


*Figure 8.8. General locations of the Caribbean barnacle (*Chthamalus proteus*) at Midway Atoll.*

It was probably introduced through either hull fouling or ballast water, although Southward et al. (1998) argues that hull fouling is more likely. It is commonly seen above the waterline on inter-island ships (Zabin, 2007). Larval dispersal could also be a natural vector for spread between the islands of the Hawaiian archipelago, now that it is established there. Although there may be some peaks of larval production, larvae are found in the water column year-round.

Surveys of MHI have found Caribbean barnacles around Kauai, Maui and Hawaii (DeFelice et al., 2001). It usually colonizes supratidal anthropogenic structures such as pier pilings and sea walls, although some individuals have been observed on intertidal boulders in the MHI. It is generally found in protected embayments and harbors, but small colonies have been found at one high energy site in Kaneohe Bay. This finding is a concern, because this species may be moving into habitat used by the native barnacle *Nesochthamalus intertextus*. At the moment, it seems the Caribbean barnacle is not competing with *N. intertextus*, but rather growing next to it. In addition, Caribbean barnacle individuals were quite small, so it was unclear whether there was an established population.

The Caribbean barnacle has been implicated in displacing another nonindigenous barnacle, *Balanus amphitrite*, in the MHI demonstrating its competitive ability (Shluker, 2003). Its rapid proliferation may reflect that it is filling an unexploited niche in the Hawaiian archipelago, in the high intertidal and splash zones. The density of colonies and the rapid pace of reproduction make the Caribbean barnacle a good competitor for space. This proliferation could alter the community structure and potentially exclude algal grazers such as protected Hawaiian limpets (e.g., *Cellana exarata, C. melanostoma, C. sandwicensis, C. talcosa*).

Styelidae, Solitary Tunicate *(Cnemidocarpa Irene)*

This species is a widespread Indo-Pacific tunicate found in Japan, the Philippines, Australia, Micronesia and Melanesia. Large specimens may reach a length of 4 cm and have a dark brown to whitish tunic with deep wrinkles that are arranged to create irregularly shaped raised areas. This species is commonly associated with fouling communities located within man-made harbors and shallow benthic habitats with rubble substrate from Kauai to the island of Hawaii (Abbott et al., 1997).

The larval stage of most solitary tunicates is brief; the larva does not feed, but concentrates on finding an appropriate place for the adult to live. The actual larvae are tadpole shaped and the muscular tail comprises two-thirds of the larval body; it is supported by a notochord and contains a nerve cord. Gravity and light-sensitive sensory vesicles along the dorsal surface of the larval body orient the animal as it swims. After a period of up to a few days, the larva will settle and attach itself to a surface using three anterior adhesive papillae. As the larva metamorphoses into an adult, the tail reabsorbs, providing food reserves for the developing animal.

This species has only been recorded from French Frigate Shoals in the Monument, where it was collected from an Autonomous Reef Monitoring Structures (ARMS) installed in 2006 (Godwin et al., 2008; Figure 8.9). Due to the short larval duration of tunicates, this species was likely transported to French Frigate Shoals by some anthropogenic means from a source location in the southeastern portion of the archipelago. Therefore this record represents recruitment to the ARMS from an undocumented established population at French Frigate Shoals.

The impacts of this species are unknown but it has the capacity to become a dominant fouling organism on any man-made substrate.

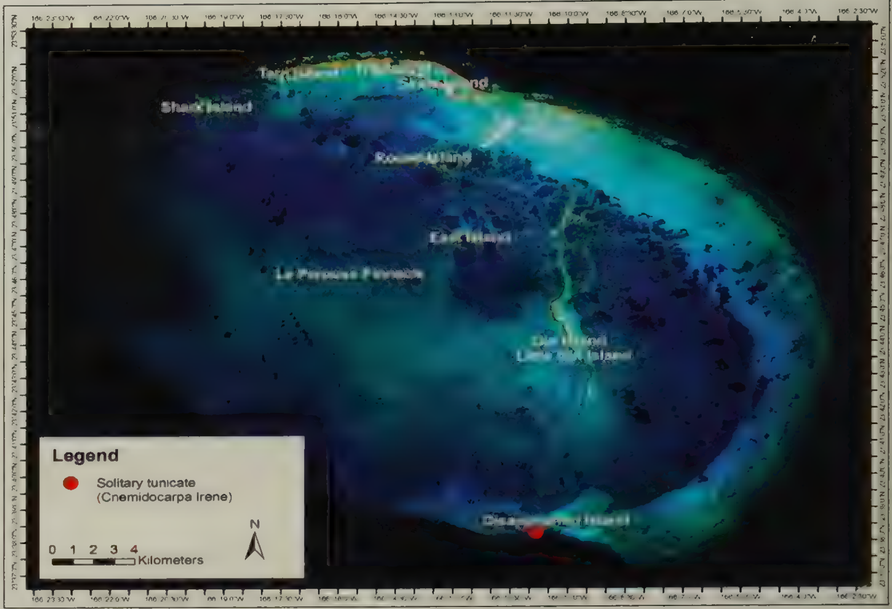


Figure 8.9. Documented location of C. irene at French Frigate Shoals.

Styelidae, Solitary Tunicate (*Polycarpa aurita*)

This solitary tunicate is pale brown with a tough and leathery tunic that is generally encrusted with worm tubes, sponges and other fouling organisms. Specimens in Hawaii only reach up to 4 cm in length but this species attains greater lengths (10-12 cm) in other areas of its Indo-Pacific range. This species is also found in the western Atlantic (Caribbean and Gulf of Mexico). It is established in the southeastern portion of the archipelago as a common species in fouling communities located within man-made harbors and the shallow and intertidal habitats of natural embayments (Abbott et al., 1997).

The larval cycle described under *C. irene* also applies to this species. Therefore, a larval cycle of only a few days exists. It was recently recorded from French Frigate Shoals from the same collections in which *C. irene* was identified (Godwin et al., 2008). These collections were part of an effort by the Coral Reef Ecosystem Division (CRED) of the Pacific Islands Fisheries Science Center in Honolulu in 2007. The focus of the efforts was to expand a 2000 project, which examined fouling organisms associated with derelict fishing gear in the NWHI (Godwin, 2000; Figure 8.10) and retrieve and quantify the organisms collected by an ARMS deployed in 2006 at French Frigate Shoals. As with *C. irene*, anthropogenic transport to French Frigate Shoals is assumed and a scenario of opportunistic recruitment to the ARMS from some established population in the lagoon is likely.

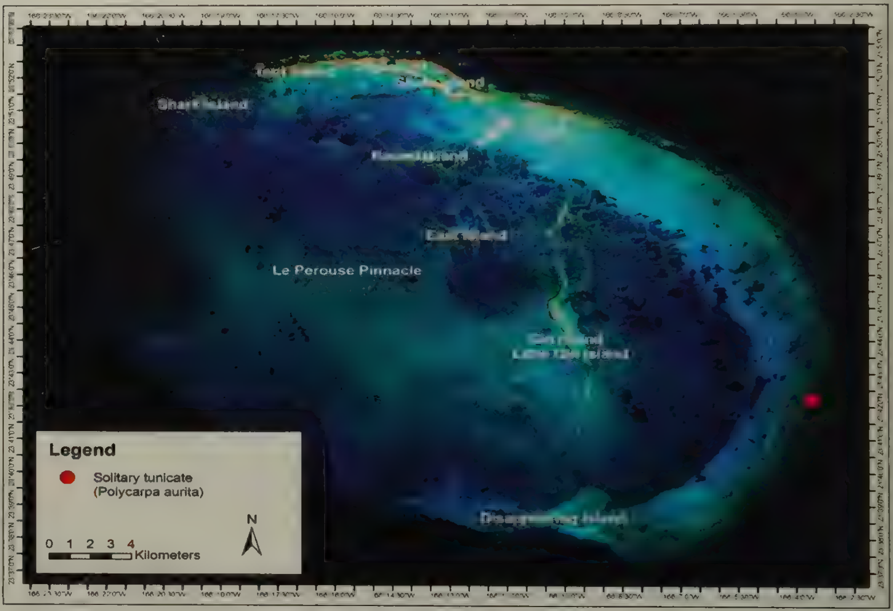


Figure 8.10. Documented location of P. aurita at French Frigate Shoals.

This species has the capacity to become an aggressive component of a fouling community on man-made surfaces, and the potential for recruitment to natural habitats is always a possibility. Recent incidences of natural tunicate populations acting invasively and overgrowing remote coral reef areas demonstrates the potential of this group of organisms to cause damage to coral reefs without direct human influence (Littler and Littler, 1995; Vargas-Angel et al., 2008)

Snowflake Coral (*Carijoa riisei*)

The snowflake coral has not been detected in the NWHI, but is a species of particular concern. It was first spotted in Pearl Harbor in 1972 (DeFelice et al., 2001), and by 1990 had been recorded around all of the MHI. Of the 343 nonindigenous marine species that have been introduced to the Hawaiian Islands, the snowflake coral may be the most successful at proliferation, as demonstrated by its distribution among the MHI, and it may exhibit some of the highest invasive potential (Grigg, 2003). It has not been sighted in the NWHI to date, but in 2007 a colony was found at Five Fathom Pinnacle (Kahng, per comm.), approximately 200 km from Nihoa Island which is the southeastern-most point of the NWHI.

This species was originally thought to be native to the Caribbean, but recent research has shown it to be more likely indigenous to the Indo-Pacific. It is likely that several slightly different species have reached the Hawaiian archipelago (Kahng, 2006).

The snowflake coral is very light sensitive; it thrives in spots that receive 10–30% ambient light, and avoids well-lit habitats. Therefore in shallow water (10–30 m), where light levels are high, it attaches to dark cracks, shaded walls or pilings, the underside of ledges and corals, lava tubes and other shaded areas. As it moves into deeper water and light levels diminish, it is found on a wider variety of habitats. At depths of 75–110 m, it has been found to explode into patches as large as 200 km^2 (Grigg, 2003). It generally attaches to hard substrates such as rocks, corals or anthropogenic structures. It does need to be positioned above the benthic layer, and away from stagnant water, as it requires some wave energy to continuously transport the zooplankton that it filters from the water for food (Godwin et al., 2006).

The snowflake coral reproduces both asexually and sexually. The polyps can split in two, allowing clones to spread and cover an entire habitable patch within several years. It can also release gametes into the water column, which once fertilized, can survive for up to 90 days (Kahng, 2006) and thus are capable of travelling long distances. This species can also spread through hull fouling, although this may not be common.

At shallow depths, the snowflake coral seems to occupy an unutilized habitat niche in Hawaii (Shluker, 2003). However at depth, it has overgrown entire beds of black coral, killing 90% of the coral surveyed in the Maui Black Coral Bed in 2001 (Grigg, 2003). Black coral harvesting generates $15 million a year in the state of Hawaiian, and the spread of the snowflake coral represents a serious threat to this industry (Godwin et al., 2006). Beyond the economic impacts, it has shown the potential to severely reduce biodiversity by blanketing entire areas.

FISHES

Three species of nonindigenous fish have been observed in the NWHI, blackline snapper (*Lutjanus fulvus*), blueline snapper (*L. kasmira*) and Peacock grouper (*Cephalopholis argus*). All three species were purposefully introduced to the MHI between 1955 and 1961 along with eight other species of groupers (Serranidae), snappers (Lujanidae) and emperor breams (Lethrinidae) from Moorea in French Polynesia. All were introduced as potential commercial species (Brock, 1960; Randall, 1987). Of the three species, blueline snapper have been the most successful in terms of distribution and abundance (Shluker, 2003).

Blackline Snapper (*Lutjanus fulvus* or Toau)

Intentionally introduced in 1956, blackline snapper has spread to all of the MHI, and into the southeastern end of the NWHI. It has been spotted at Nihoa and French Frigate Shoals (Shluker, 2003; Figure 8.11). It has fairly low abundance, possibly due to its exploitation for food (Shluker, 2003). Blueline snapper (*L. kasmira*) was introduced around the same time, but it has spread much faster than blackline snapper, despite the many biological similarities between the two species. Scientists are unsure how to explain the difference in range expansion.

Blackline snapper is a reef fish, generally found in the lagoons or outer reef slopes and usually at depths of 1–40 m, but it has been seen as deep as 75 m. It has a temperature tolerance of 20–28°C and spawns year-round (http://www.larvalbase.org), increasing its chances of larval dispersal. Ecological impacts are unstudied.

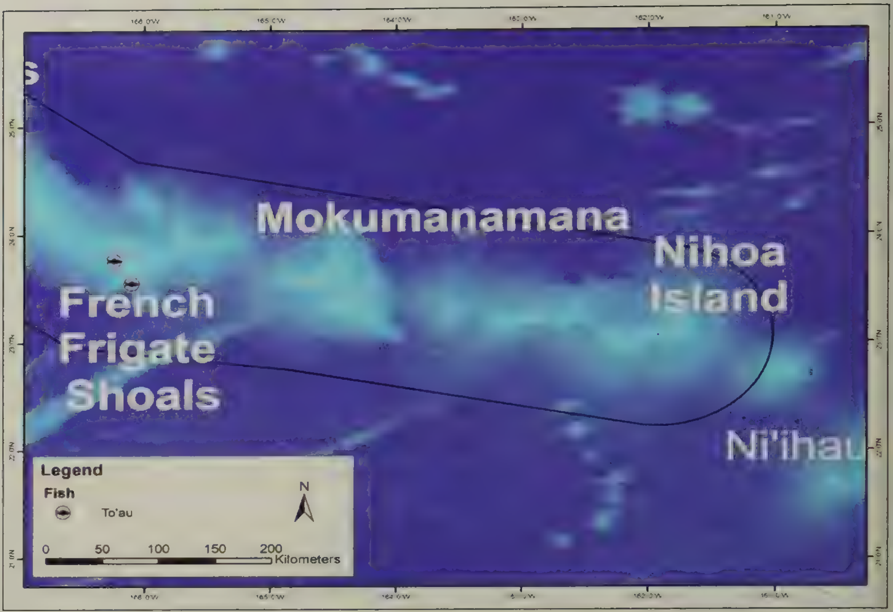


*Figure 8.11. Documented distribution of blackline snapper (*Lutjanus fulvus*) in the NWHI.*

Blueline Snapper
(Lutjanus kasmira or Taape)

Blueline snapper has been detected throughout the NWHI, including Nihoa, Mokumanamana, French Frigate Shoals, Maro Reef, Laysan Island and Midway Atoll (Friedlander et al., 2005). It likely migrated from the MHI where it was intentionally introduced to Oahu in 1955. From the initial population of 3,200 individuals brought from French Polynesia, the fish has spread throughout the full length of the Hawaiian archipelago (Oda and Parrish, 1982; Randall et al., 1993; Figure 8.12) and is now one of the most conspicuous and abundant species in the fish community. Friedlander et al. (2002) found blueline snapper was the second most abundant species by number and biomass over hard substrate in Hanalei Bay, Kauai.

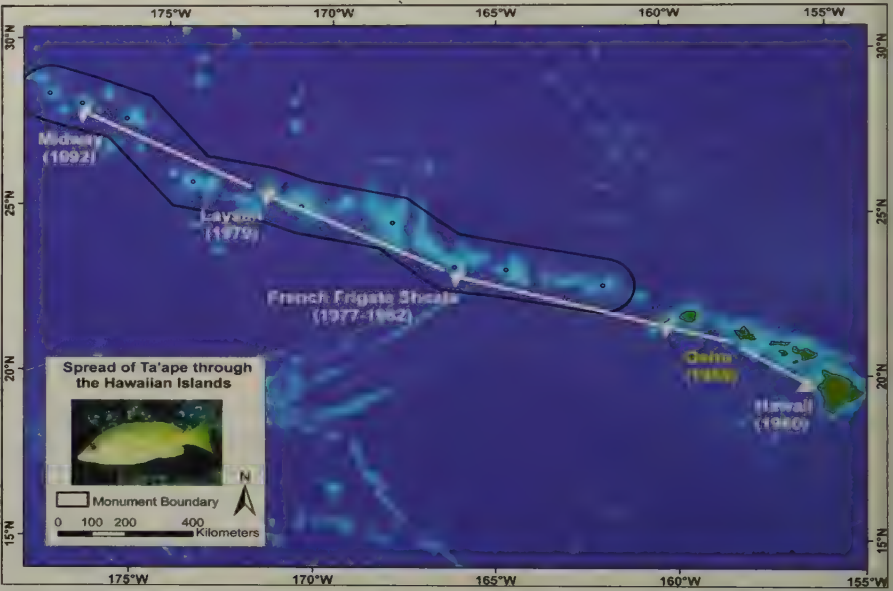


*Figure 8.12. Documented distribution of blueline snapper (*Lutjanus kasmira*) in the NWHI. Source: Sladek Nowlis and Friedlander, 2004.*

Due to its abundance and the concern that blueline snapper might impact native fish, more effort has been spent studying its ecology compared to other similar nonindigenous species. Blueline snapper is generally found in lagoons and outer reef slopes at depths from 2-70 m, but it has been seen as deep as 256 m. Friedlander et al. (2002) found the species to be abundant over habitats like deep slope, spur and groove and shallow slope, but it was also found in lesser quantities in the complex back reef. A more recent report indicated that blueline snapper is also common among algal plain habitats (C. Menza, pers. comm.). These low relief habitats dominated by algae (macroalgae and crustose coralline algae), may make up a considerable proportion of the deeper benthic habitats in the NWHI where coral are rare. Friedlander et al. (2002) have also shown that blueline snapper utilize sand habitats for feeding and the species may undergo an ontogenetic habitat shift.

The blueline snapper was never accepted into the local diet, and many fishermen believe it out competes native fish for resources and fishing bait. There is little scientific evidence to back this conclusion (but see Schumacher and Parrish, 2005), which leads to disagreement and debate between scientists and fishermen as to the effects of the blueline snapper on native species (Shluker, 2003).

Peacock Grouper (*Cephalopholis argus* or Roi)

The Peacock grouper was introduced from French Polynesia in 1956 as a food species. Since then, it has spread throughout the MHI, and has been seen at Nihoa, Mokumanamana and French Frigate Shoals in the NWHI (Shluker, 2003; Godwin et al., 2006; Figure 8.13).

It is found in lagoons and seaward reef habitats, at depths of 1–40 m, although it generally prefers depths of 10 m or less (Godwin et al., 2006).

Although originally sought by fishermen, its popularity declined after incidences of ciguatera poisoning increased and is now considered by many fishermen as unsafe to eat (Godwin et al., 2006). Without fishing pressure, the Peacock grouper has grown abundant and could impact native reef fishes through predation as well as competition for space and resources. However, there is little scientific research on the effects due to Peacock grouper, and thus no conclusive evidence has been gathered.

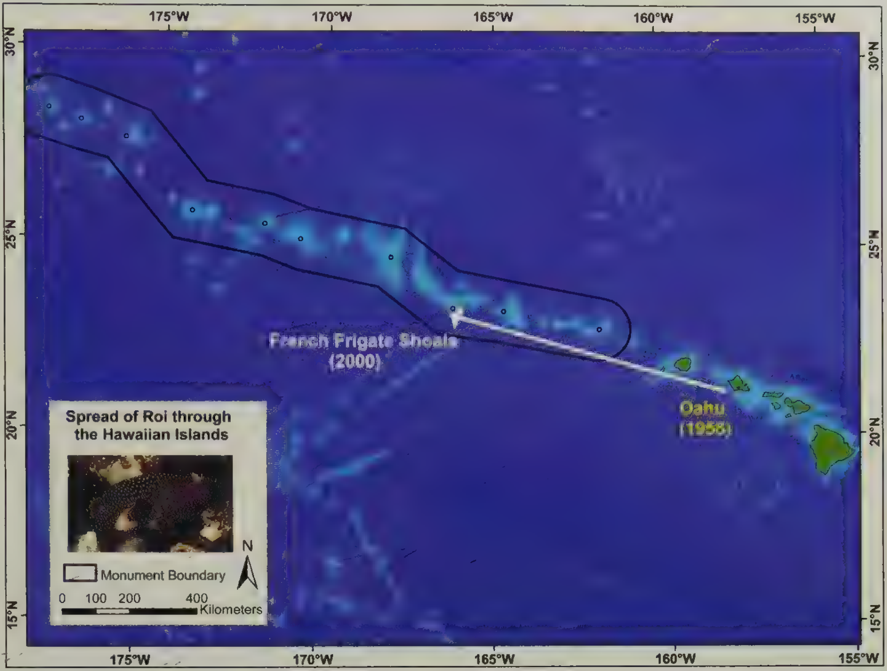


*Figure 8.13. Documented distribution of the Peacock grouper (*Cephalopholis argus*) in the NWHI. Source: Sladek Nowlis and Friedlander, 2004.*

MANAGEMENT

PMNM has taken active steps to mitigate the threats of NIS, including ballast discharge prohibition, hull inspections and cleaning, snorkel/dive gear treatment and luggage inspection of air passengers. Action plans consisting of multiple strategies and activities address PMNM priority management needs. One of the PMNM's 22 action plans is "to detect, control, eradicate where possible, and prevent the introduction of alien species into the Monument". PMNM has also undertaken research to develop knowledge of baseline conditions and detect NIS introductions. Early detection greatly increases the probability of NIS control and possibly eradication (e.g., Pyne, 1999).

EXISTING DATA GAPS

The primary data gap for nonindigenous and invasive species in the NWHI is a complete survey of nonindigenous species across habitats. Surveys need to have a greater spatial distribution to have a more complete picture of the nonindigenous and invasive species populations. The following are key datasets needed for management and future research efforts:

- Species inventory;
- Population size;
- Rate of spread;
- Spatial distribution; and
- Habitat requirements and natural history information for established populations to use in habitat suitability models.

REFERENCES

Abbott, D.P., A.T. Newberry, and K.M. Morris. 1997. Section 6B: Ascidians (Urochordata). Reef and Shore Fauna of Hawaii. Bishop Museum Special Publication. 64 (6B). 64 pp.

Botany, University of Hawaii Manoa. 2001. Algae: Invasive alien *Acanthophora spicifera*. Available from Internet URL: http://www.hawaii.edu/reefalgae/invasive_algae/rhodo/acanthophora_spicifera.htm.

Botany, University of Hawaii Manoa. 2001. Algae: Invasive alien *Hypnea musciformis*. Available from Internet URL: http://www.hawaii.edu/reefalgae/invasive_algae/rhodo/hypnea_musciformis.htm.

Brock, V. 1960. The introduction of aquatic animals into Hawaiian water. Int. Revue Hydrobiol. 45: 463-480.

Brostoff, W. 1989. *Avrainvillea amadelpha* (Codiales, Chlorophyta) from Oahu Hawaii. Pac Sci 43: 166-9.

Coles, S.L., P.R. Reath, K. Longenecker, H. Bolick, and L.G. Eldredge. 2004. Assessment of nonindigenous marine species in harbors and on nearby coral reefs on Kaua'i, Moloka'i, Maui and Hawaii. Final report prepared for the Hawai'i Community Foundation and the U. S. Fish and Wildlife Service, Bishop Museum, Hawaii Biological Survey, Bishop Museum Technical Report No. 29a.

DeFelice, R.C., S.L. Coles, D. Muir, and L.G. Eldredge. 1998. Investigation of the marine communities of Midway Harbor and adjacent lagoon, Midway Atoll, Northwestern Hawaiian Islands. Bishop Museum, Hawaii Biological Survey Contribution No. 1998-014.

DeFelice, R.C., L.G. Eldredge, and J.T. Carlton. 2001. Nonindigenous marine invertebrates. Contribution No. 2001-005 to the Hawaii Biological Survey. Bishop Museum, Hawaii Biological Survey, Bishop Museum Technical Report No. 21.

DeFelice, R.C., D. Minton, and L.S. Godwin. 2002. Records of shallow-water marine invertebrates from French Frigate Shoals, Northwestern Hawaiian Islands, with a note on non-indigenous species. Report to the U.S. Fish and Wildlife Service. Bishop Museum, Hawai'i Biological Survey, Bishop Museum Technical Report No. 23.

Doty, M. S. 1961. Acanthophora, a possible invader of the marine flora of Hawaii. Pac. Sci. 15(4): 547- 552.

Draft Environmental Impact Statement and Management Plan for the Northwestern Hawaiian Islands Proposed National Marine Sanctuary. 2006. Available from Internet URL: http://hawaiireef.noaa.gov/management/mp.html.

Eldredge, L.G. 2003. Coral Reef Invasions. In: De Poorter, M. (Ed.). 2003. Aliens (17): 9.

Eldredge, L.G. and J.T. Carlton. 2002. Hawai'i marine bioinvasions: a preliminary assessment. Pacific Science 56(2): 211-212.

Eldredge, L.G. 2005. Assessment of the Potential Threat of the Introduction of Marine Nonindigenous Species in the Northwestern Hawaiian Islands. Final Report Prepared for Environmental Defense, Waimanalo, Hawaii. 8 pp. Contribution No. 2005-001 to the Hawaii Biological Survey.

Friedlander, A.M, G. Aeby, S. Balwani, B. Bowen, R. Brainard, A. Clark, J. Kenyon, J. Maragos, C. Meyer, P. Vroom, and J. Zamzow. 2008. The State of Coral Reef Ecosystems of the Northwestern Hawaiian Islands. Pp. 263-306. In: J.E. Waddell and A.M. Clarke (eds.), The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.

Friedlander, A.M, G. Aeby, R. Brainard, A. Clark, E. DeMartini, S. Godwin, J. Kenyon, R. Kosaki, J. Maragos, and P. Vroom. 2005. The State of the Coral Reef Ecosystems of the Northwestern Hawaiian Islands. Pp. 270-311. In: J. Waddell (ed.), The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2005. NOAA Technical Memorandum NOS NCCOS 11. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 522 pp.

Friedlander, A.M., J.D. Parrish and R.C. Defelice. 2002. Ecology of the introduced snapper *Lutjanus kasmira* (Forsskal) in the reef fish assemblage of a Hawaiian bay, Journal of Fish Biology 60(1): 28-48.

Godwin, L.S. 2000. Northwestern Hawaiian Islands derelict fishing net removal project: survey of marine organisms associated with net debris. Report submitted to NOAA-NMFS Coral Reef Ecosystem Investigation. 11 pp.

Godwin, L.S. L. Harris, A. Charette and R. Moffitt. 2008. The marine invertebrate species associated with the biofouling of derelict fishing gear in the Papahanoumokuakea–Marine National Monument. Report submitted to NOAA-NMFS, PIFSC, Coral Reef Ecosystem Division. (In Review).

Godwin, L.S., L.G. Eldredge, and K. Gaut. 2004. The Assessment of Hull Fouling as a Mechanism for the Introduction and Dispersal of Marine Alien Species in the Main Hawaiian Island. Final report submitted to the Hawaii Coral Reef Initiative Research Program. Bishop Museum Technical Report 28. Contribution 2004-015 to the Hawaii Biological Survey.

Godwin, S., K.S. Rodgers, and P.L. Jokiel. 2006. Reducing potential impact of invasive marine species in the northwestern Hawaiian islands marine national monument. Report to: Northwest Hawaiian Islands Marine National Monument Administration.

Grigg, R.W. 2003. Invasion of a deep black coral bed by an alien species, *Carijoa riisei*, off Maui, Hawaii. Coral Reefs 22:121–122.

Kahng S.E. 2006. Ecology and ecological impact of an alien octocoral, *Carijoa riisei*, in Hawaii. PhD thesis, University of Hawaii.

Kilar, J.A. and J. McLachlan. 1986. Ecological Studies of the Alga, *Acanthophora spicifera* (Vahl) Borg. (Ceramiales: Rhodophyta): Vegetative Fragmentation. J. Exp. Mar. Biol. Ecol. 104: 1-21.

Littler M.M. and D.S. Littler. 1995. A colonial tunicate smothers corals and coralline algae in the Great Astrolabe Reef, Fiji. Coral Reefs 14: 148–149.

Oda, D. K. and J.D. Parrish. 1982. Ecology of commercial snappers and groupers introduced to Hawaiian reefs. Pp: 59–67. In Proceedings of the Fourth International Coral Reef Symposium Vol. 1 (E.D. Gomez, C.E. Birkeland, R.W. Buddemeier, R.E. Johannes, J.A., Jr. Marsh, and R.T. Tsuda, eds). Quezon City, Philippines: Marine Sciences Center, University of the Philippines.

Preskitt, L. 2002. *Acanthophora spicifera* (Vahl) Borgesen 1910. Invasive Marine Algae of Hawaii. University of Hawaii at Manoa. Fact sheet available from: http://www.hawaii.edu/reefalgae/invasive_algae/rhodo/acanthophora_spicifera.htm [Accessed 1 December 2008]

Pyne, R. 1999. The black striped mussel (*Mytilopsis sallei*) infestation in Darwin: A clean-up strategy. Ecoports Monogr. Ser. No. 19:77–83.

Randall, J. E. 1987. Introductions of marine fishes to the Hawaiian islands. Bull. Mar. Sci. 41(2): 490–502.

Randall, J.E., J.L. Earle, T. Hayes, C. Pittman, M. Severns, and R.J.F. Smith. 1993. Eleven new records and validations of shore fishes from the Hawaiian Islands. Pac. Sci. 47(3): 222–239.

Rodgers, K. and E. Cox. 1999. The rate of spread of the introduced Rhodophytes, *Kappaphycus alvarezii* (Doty), *Kappaphycus striatum Schmitz* and *Gracilaria salicornia C. ag*. and their present distributions in Kane'ohe Bay, Oahu, Hawaii. Pacific Science, (53)3: 232-241.

Russell, D.J. 1987. Introductions and establishment of alien marine algae. Bull Mar Sci, 42: 641-642.

Russell, D.J. 1992. The ecological invasion of Hawaiian reefs by two marine red algae, *Acanthophora spicifera* (Vahl) Boerg and *Hypnea musciformis* (Wulfen) J. Ag., and their association with two native species, *Laurencia nidifica* J. Ag. and *Hypnea cervicomis* J. Ag. ICES mar Sci Symp (Act Symp) 194: 110-125.

Schumacher, B. D. and J. D. Parrish. 2005. Spatial relationships between an introduced snapper and native goatfishes on Hawaiian reefs. Biological Invasions 7: 925-933.

Shluker, A.D. 2003. State of Hawaii Aquatic Invasive Species Management Plan. The Department of Land and Natural Resources, Division of Aquatic Resources.

Smith, J.E., C.L. Hunter, and C.M. Smith. 2002. Distribution and Reproductive Characteristics of Nonindigenous and Invasive Marine Algae in the Hawaiian Islands. Pacific Science 56 (3):299-315.

Smith J.E., Hunter C.L., Conklin E.J., R. Most, T. Sauvage, C. Squair, C.M. Smith. 2004. Ecology of the invasive red alga *Gracilaria salicornia* (Rhodophyta) on Oahu, Hawaii. Pac Sci 58: 325–343.

Southward, A.J., R.S. Burton, S.L. Coles, P.R. Dando, R. DeFelice, J. Hoover P.E. Parnell, T. Yamaguchi, and W.A. Newman. 1998. Invasion of Hawaiian shores by an Atlantic barnacle. Mar. Ecol. Prog. Ser. 165: 119-126.

Vargas-Angel, B., L.S. Godwin, J. Asher, and R.E. Brainard. 2008. Invasive didemnid tunicate spreading across coral reefs at remote Swains Island, American Sāmoa. Coral Reefs (In Press).

Waddell, J.E. and A.M. Clarke (eds.). 2008. The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.

Woo, M.M.L. 2000. Ecological impacts interactions of the introduced red alga, *Kappaphycus striatum*, in Kaneohe Bay, Oahu, Masters Thesis, University of Hawaii at Manoa, Honolulu, Hawaii.

Zabin, C. 2007. A tale of three seas: consistency of natural history traits in a Caribbean–Atlantic barnacle introduced to Hawaii. Biological Invasions 9: 523-544

Zabin, C.J., J.T. Carlton, and L.S. Godwin. 2004. First report of the Asian sea anemone *Diadumene lineate* from the Hawaiian Islands. Bishop Museum Occasional Papers 79: 54-58.

PERSONAL COMMUNICATIONS

Abbott, I. The University of Hawaii, HI, USA
Godwin, S. Papahanaumokuakea Marine National Monument Honolulu, HI, USA
Kahng, S. Hawaii Pacific University, College of Natural Sciences, Waimanalo, HI, USA
Menza, C. NOAA Biogeography Branch, Silver Spring, MD, USA

WEBSITES

University of Hawaii at Manoa • Botany Department and Bishop Museum. Invasive Marine Algae of Hawaii. 2009 http://hawaii.edu/reefalgae/invasive_algae/index.htm

German Ministry for Economic Cooperation and Development (BMZ). 2006. http://www.larvalbase.org

Connectivity and Integrated Ecosystem Studies

Alan Friedlander[1,2], Donald Kobayashi[3], Brian Bowen[4], Carl Meyers[4], Yannis Papastamatiou[4], Edward DeMartini[3], Frank Parrish[3], Eric Treml[5], Carolyn Currin[6], Anna Hilting[6], Jonathan Weiss[3,7], Chris Kelley[8], Robert O'Conner[7], Michael Parke[3], Randy Clark[1], Rob Toonen[4] and Lisa Wedding[1,9]

INTRODUCTION

Population connectivity is the exchange of individuals among geographically separated subpopulations. Defining the scale of connectivity among marine populations and determining the factors driving this exchange are critical to our understanding of the population dynamics, genetic structure and biogeography of reef fishes (Cowen et al., 2006). Although larvae have the potential for long-distance dispersal, evidence is mounting that larval dispersal may be limited and marine subpopulations may be more isolated over smaller spatial scales than previously thought (Cowen et al., 2007). The rates, scale and spatial structure of successful exchange, or connectivity, among local populations of marine organisms drive population replenishment and, therefore, have profound implications for population dynamics and genetics of marine organisms, spatially oriented resource management (e.g., marine protected areas) and the spread of invasive species. Despite the importance of this issue in understanding population dynamics and effectively managing these species or areas (e.g., Crowder et al., 2000; Valles et al., 2001), larval connectivity in the Northwestern Hawaiian Islands (NWHI) is relatively unknown. The uniquely endemic fish and other marine faunas of the Hawaiian Archipelago (Hourigan and Reese, 1987) and the extreme expression of endemism in the NWHI (DeMartini and Friedlander, 2004) make such information critically important for the Hawaiian Archipelago and specifically the Papahanaumokuakea Marine National Monument (PMNM).

LARGE-SCALE POPULATION CONNECTIVITY MODELS FROM OCEAN CURRENTS

For many marine species, population connectivity is determined largely by ocean currents transporting larvae and juveniles between distant patches of suitable habitat. To evaluate the patterns in connectivity throughout the Hawaiian Archipelago, a spatially explicit biophysical model was used to simulate coral dispersal between reefs spanning the archipelago for three different years (a strong El Niño year- 1997, a strong La Niña year- 1999, and a neutral year- 2001; Treml et al., 2008). Simulated connectivity was summarized seasonally and across years.

This two-dimensional Eulerian advection–diffusion model of coral dispersal incorporates realistic surface current velocity data and estimates of planktonic larval duration (PLD). In this model, the probability of potential dispersal to a reef is the product of: 1) the hydrodynamic arrival probability, 2) larval mortality and 3) the settlement probability. The spatially explicit hydrodynamic model and resultant arrival probabilities incorporate reef topology, ocean current variability and spawning location.

Summary of Patterns Across Hawaii with Reference to Spatial Data

Results indicate that the scale of dispersal is on the order of 50-150 km, which is consistent with recent studies in the Caribbean (Cowen et al., 2006). On average, the Main Hawaiian Islands (MHI) appear to be consistently connected and well mixed at levels above 1/10,000 per season for hypothetical larvae with a PLD of 60 days (Figure 9.1). The northwestern most atolls (Kure, Midway, and Pearl and Hermes) are also constantly and strongly connected throughout the dispersal scenarios. The entire Hawaiian archipelago appears completely

---

1. NOAA/NOS/NCCOS/CCMA Biogeography Branch
2. The Oceanic Institute
3. NOAA/NMFS/Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division
4. Hawaii Institute of Marine Biology
5. World Wildlife Fund Fuller Fellow, School of Integrative Biology, University of Queensland, St. Lucia, QLD Australia
6. NOAA/NOS-Beaufort Lab
7. Joint Institute of Marine and Atmospheric Research
8. Hawaii Undersea Research Lab
9. University of Hawaii at Manoa

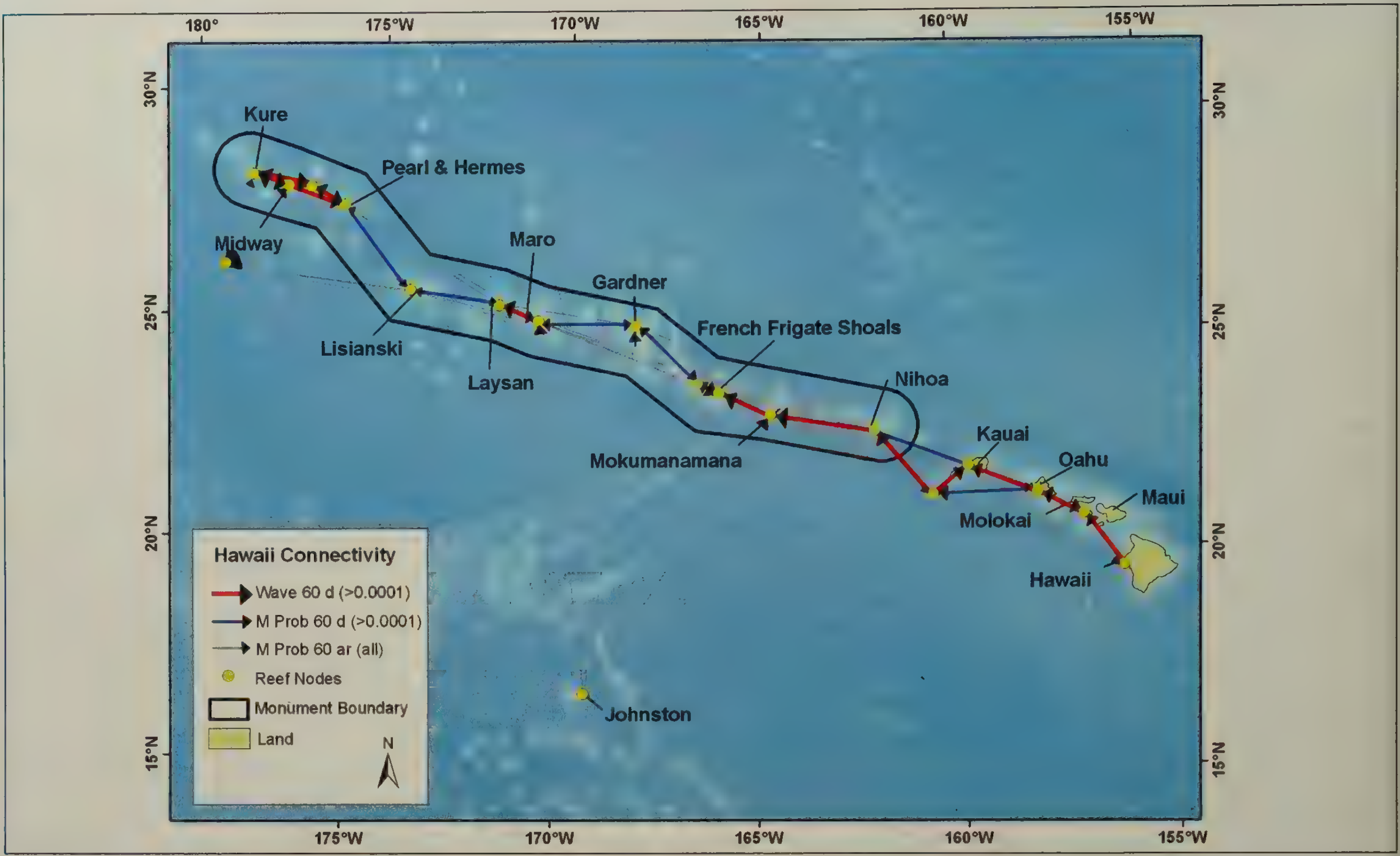


Figure 9.1. Dispersal pathways in the Hawaiian Archipelago based on Eulerian advection-diffusion models (adapted from Treml et al., 2008). Coral reef habitat is represented by nodes within the graph framework. When larvae from a source reef reach a downstream reef site, a dispersal connection is made. This dispersal connection and direction is represented by an arrow, or 'edge' within the graph. The thickness of the arrow reflects the strength of connection. Source: Treml, unpublished data; map: L. Wedding.

connected at similar levels for at least one season out of the years modeled, albeit predominately in a northwesterly direction. For connectivity via rafting and for those organisms that have a longer PLD or higher survival while dispersing, the hydrodynamics around the Hawaiian Islands provide opportunity for dispersal and mixing throughout. In addition, long distance larval dispersal from Johnston Atoll to the mid-Hawaii archipelago appears to be possible during unique seasons: La Niña, July – September and October – December; neutral years, July – September, with the strongest connection in October – December during La Niña years.

Larval Retention Versus Larval Subsidy

Metapopulation connectivity in the Hawaiian Archipelago is poorly understood, and this hinders effective management and assessment of living marine resources in the region. Pelagic transport was investigated using high-resolution ocean current data and computer simulation (Kobayashi, in review). Adjacent strata in the archipelago appeared well connected via simulated pelagic larval transport regardless of larval duration, while connectivity of more distant strata appear mediated by larval duration (Figures 9.2-9.8). Retention (defined as the return of natal propagules) is contrasted with reception or subsidy (the influx of propagules from other sources). These two processes appear to be decoupled based on examination of archipelago-wide simulations. Single-generation and multigeneration effects of connectivity were considered using a simple population dynamics model driven by the dispersal kernel probability estimates. The PMNM appears to be largely self-sustaining based on these results, with differential input to certain inhabited islands farther southward in the archipelago depending on the pelagic larval duration.

Retention rate (as a fraction of propagules released) ranged from a low of 0.39% at Lanai, to a high of 17.24% for the island of Maui (Figure 9.8). When retention and subsidy were pooled to estimate total settlement per unit of habitat, settlement ranged from a low of 6,288 settlers per pixel at Kure Atoll to a high of 149,192 settlers per pixel at Northampton. The high settlement rate at the relatively small Northampton is attributed mostly to subsidy.

The biological significance of the PMNM to the entire Hawaiian Archipelago can be considered from the connectivity probabilities and the metapopulation analysis. The equilibrium metapopulation composition predicted after many generations can be useful in understanding the importance of adjacent or even nonadjacent geographic strata. For organisms with short larval duration (15 days), a relatively narrow transitional region including Nihoa, Middle Bank, Niihau and Kauai is composed of settlers from both the PMNM and MHI regions. Areas farther north and south have negligible crossover. However, at longer PLDs (90 days), nearly all regions throughout the MHI have some component of the settlers derived from the PMNM, whereas most of the PMNM is self-seeding until approximately Mokumanamana is reached.

While the effects of Maro and Gardner can be attributed to their relatively large reproductive output in the simulations, other large areas do not contribute similarly to the equilibrium composition, which is a model consequence of dispersal kernel probabilities operating over many generations. When the effect of habitat size is removed by scaling total retention and reception by habitat pixel counts, this yields evidence of a decoupling of retention and reception processes. This implies that there is very little, if any, physical (geographic or oceanographic) relationship between factors which promote effective natal larval retention and factors which promote influx of outside larval reception. Settlement and recruitment studies which ignore propagule origins may have difficulty in relating observed patterns to oceanographic features for this very reason. Since neither measure is a strong proxy for the other, the futility of understanding transport dynamics given the single aggregated measure is readily apparent. The need for additional genetics studies and other stock identification markers for sourcing of incoming propagules is urgent (e.g., Bernardi et al., 2002; Schultz et al., 2007).

Clearly since the connectivity measures appear high for adjacent habitats, over evolutionary time the genetic connectivity might be more pronounced than inferred here. This could be particularly important at the southern boundary of the PMNM, with a protected spawning source able to effectively seed areas to the south over time via a "stepping stone" effect, not immediately apparent from examining the pair-wise connectivity values. This gradual diffusive process could lead to much more connectivity than that described by a single generation.

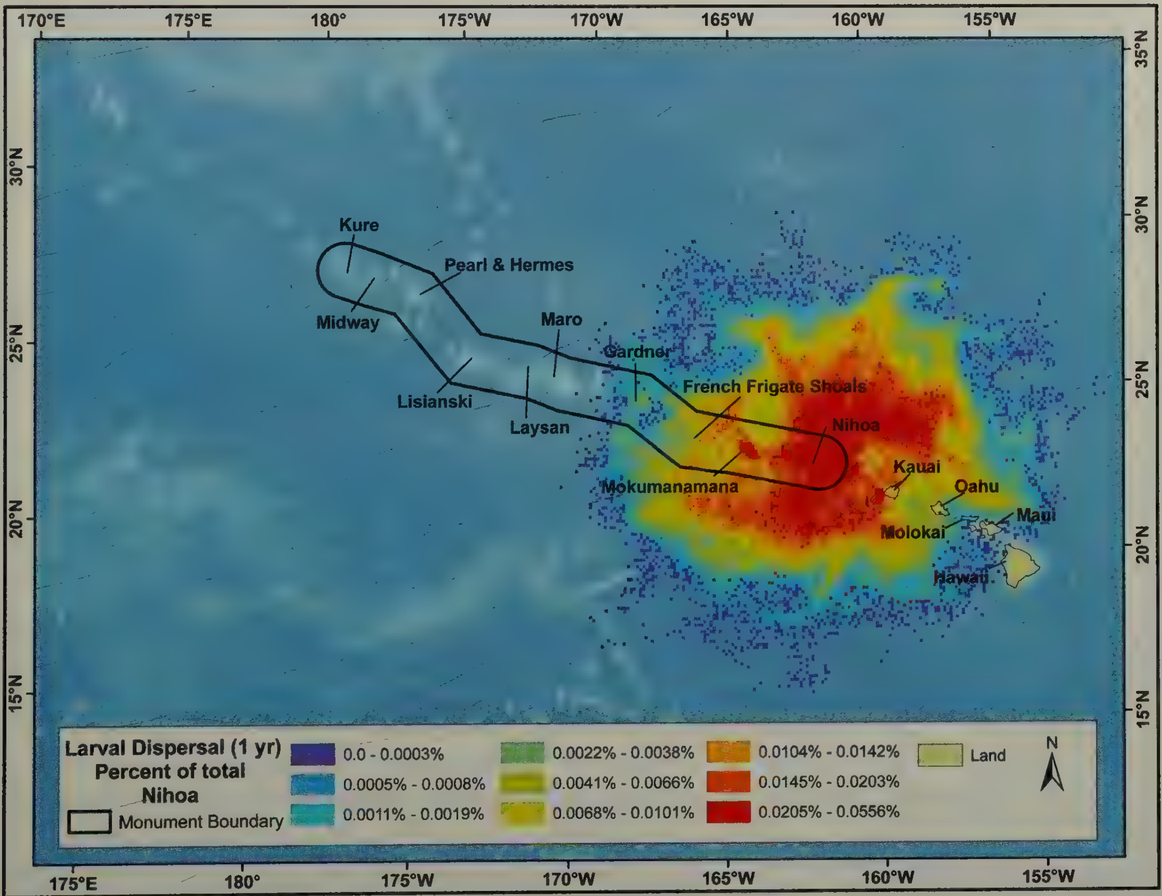


Figure 9.2. Larval dispersal (45 day PDL) one year after being released from Nihoa Island. Source: Kobayashi, in review; map: L. Wedding.

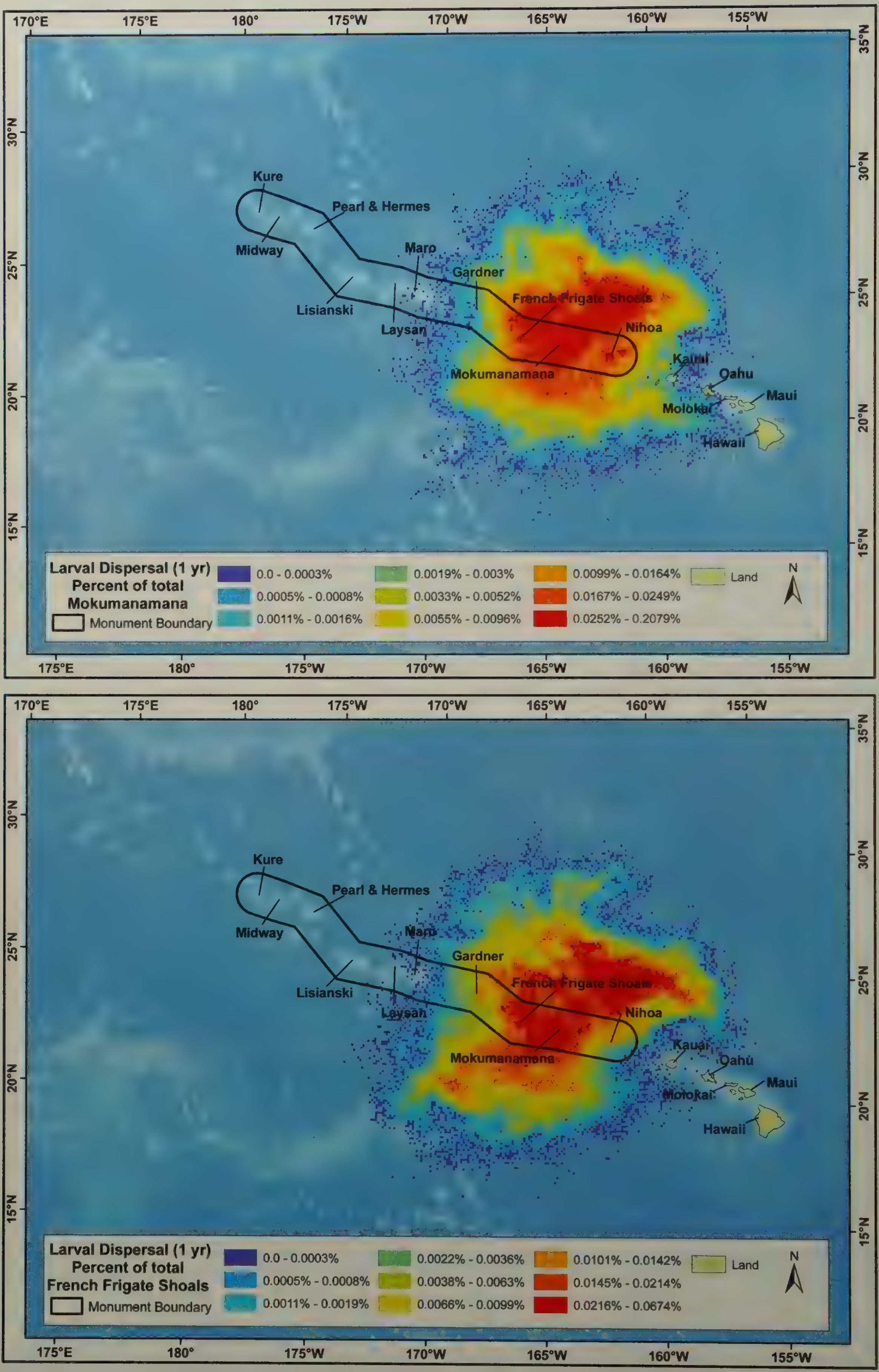


Figure 9.3. Larval dispersal (45 day PDL) one year after release from Mokumanamana (top) and French Frigate Shoals (bottom). Source: Kobayashi, in review; maps: L. Wedding.

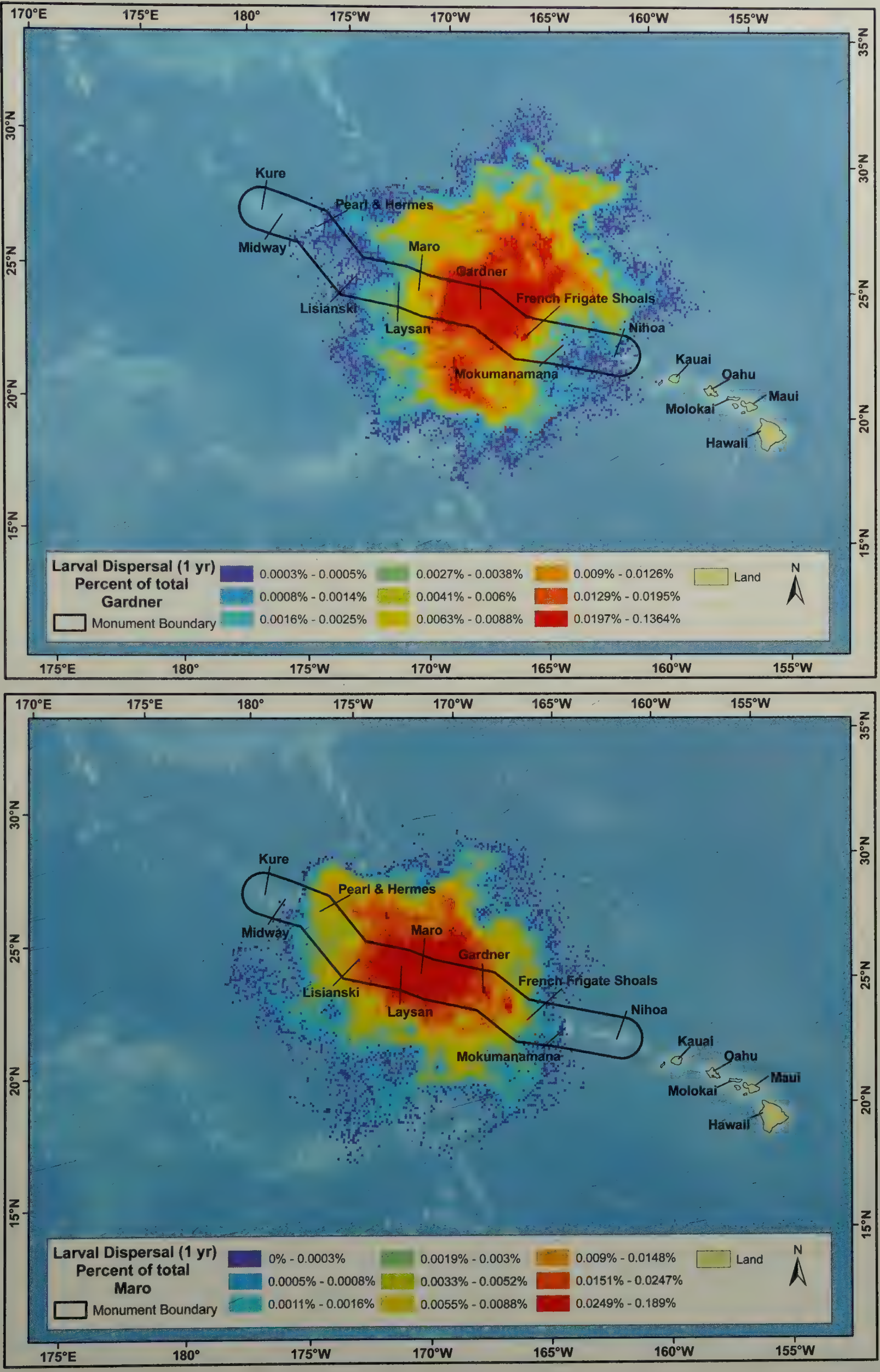


Figure 9.4. Larval dispersal (45 day PDL) one year after release from Gardner Pinnacles (top) and Maro Reef (bottom). Source: Kobayashi, in review; maps: L. Wedding.

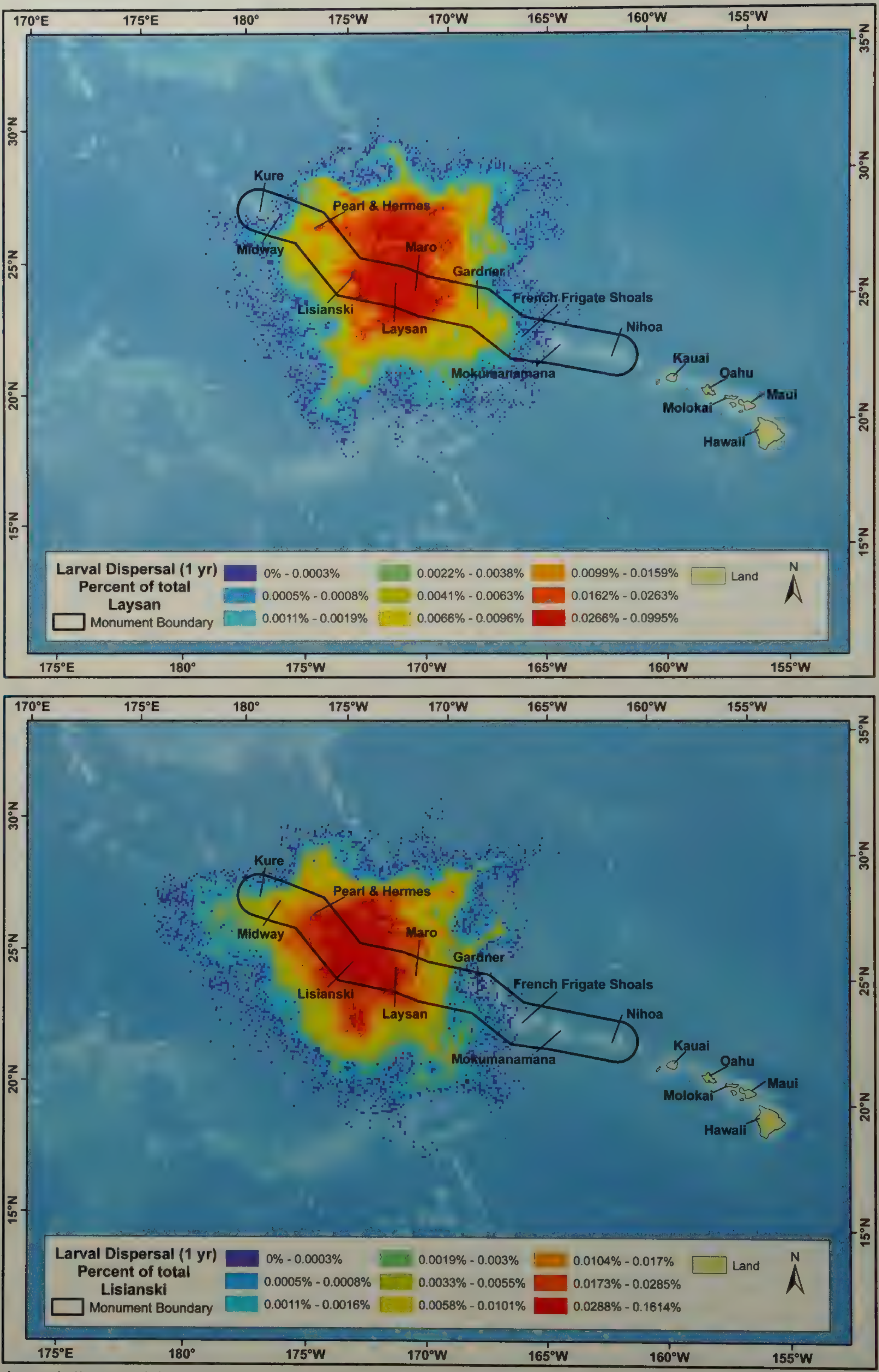


Figure 9.5. Larval dispersal (45 day PDL) one year after release from Laysan Island (top) and Lisianski Island (bottom). Source: Kobayashi, in review; maps: L. Wedding.

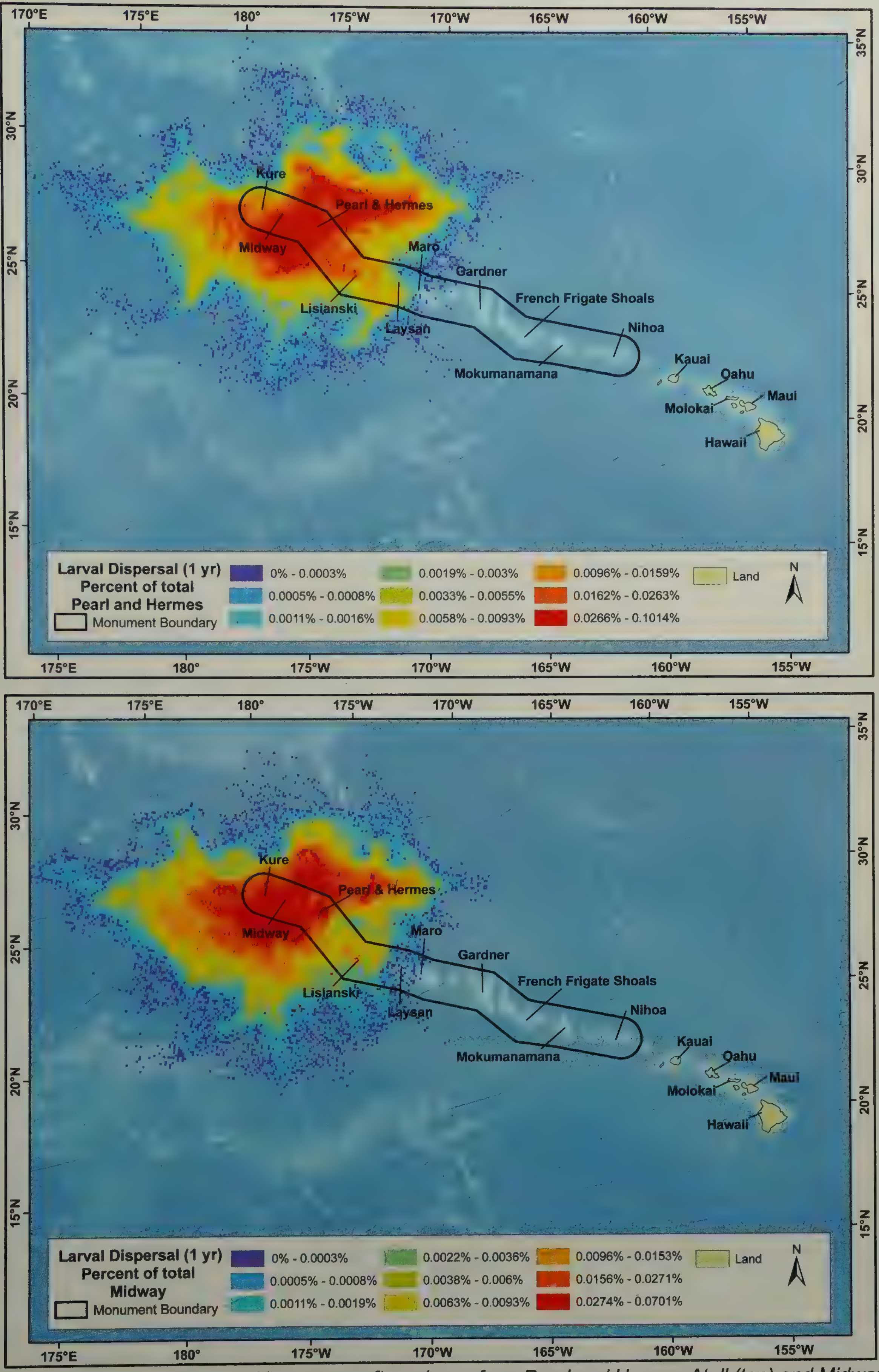


Figure 9.6. Larval dispersal (45 day PDL) one year after release from Pearl and Hermes Atoll (top) and Midway Atoll (bottom). Source: Kobayashi, in review; maps: L. Wedding.

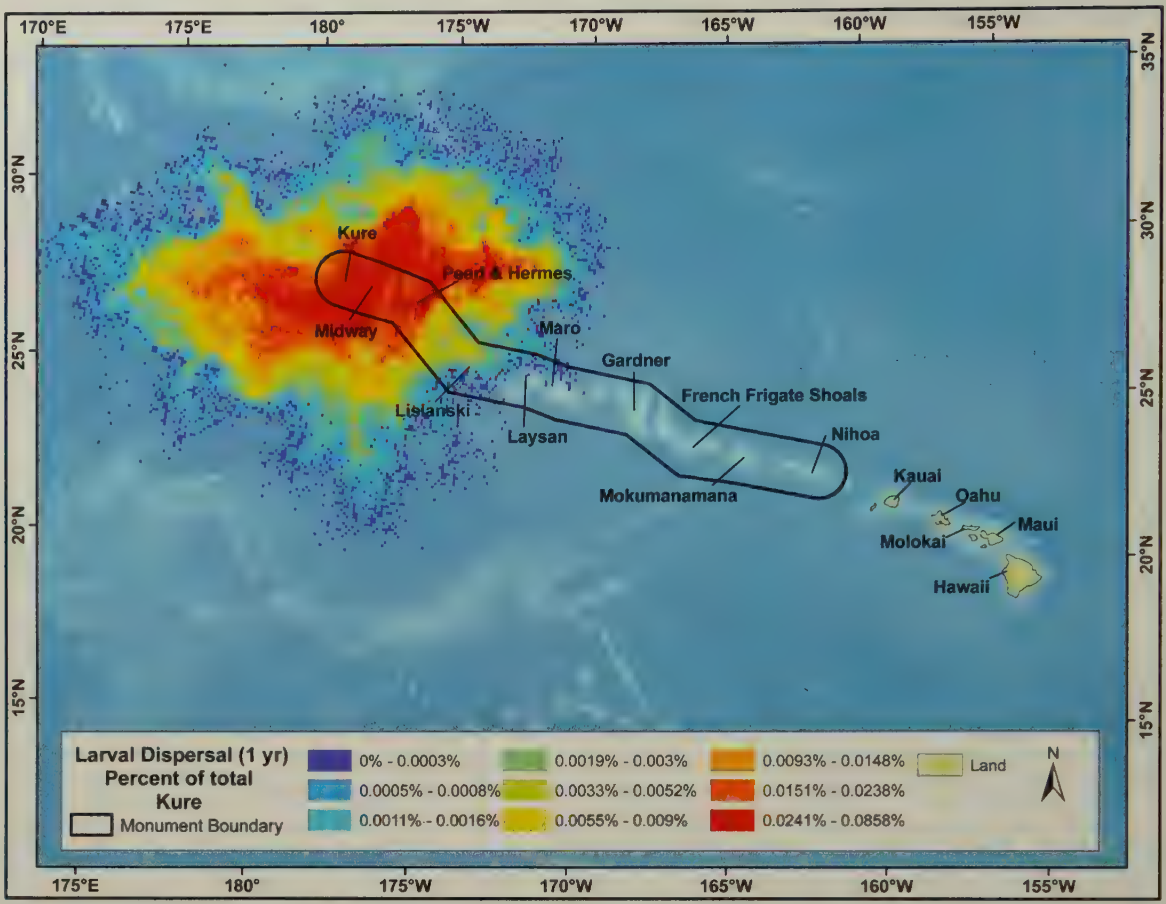


Figure 9.7. Larval dispersal (45 day PDL) one year after being released from Kure. Source: Kobayashi, in review; map: L. Wedding.

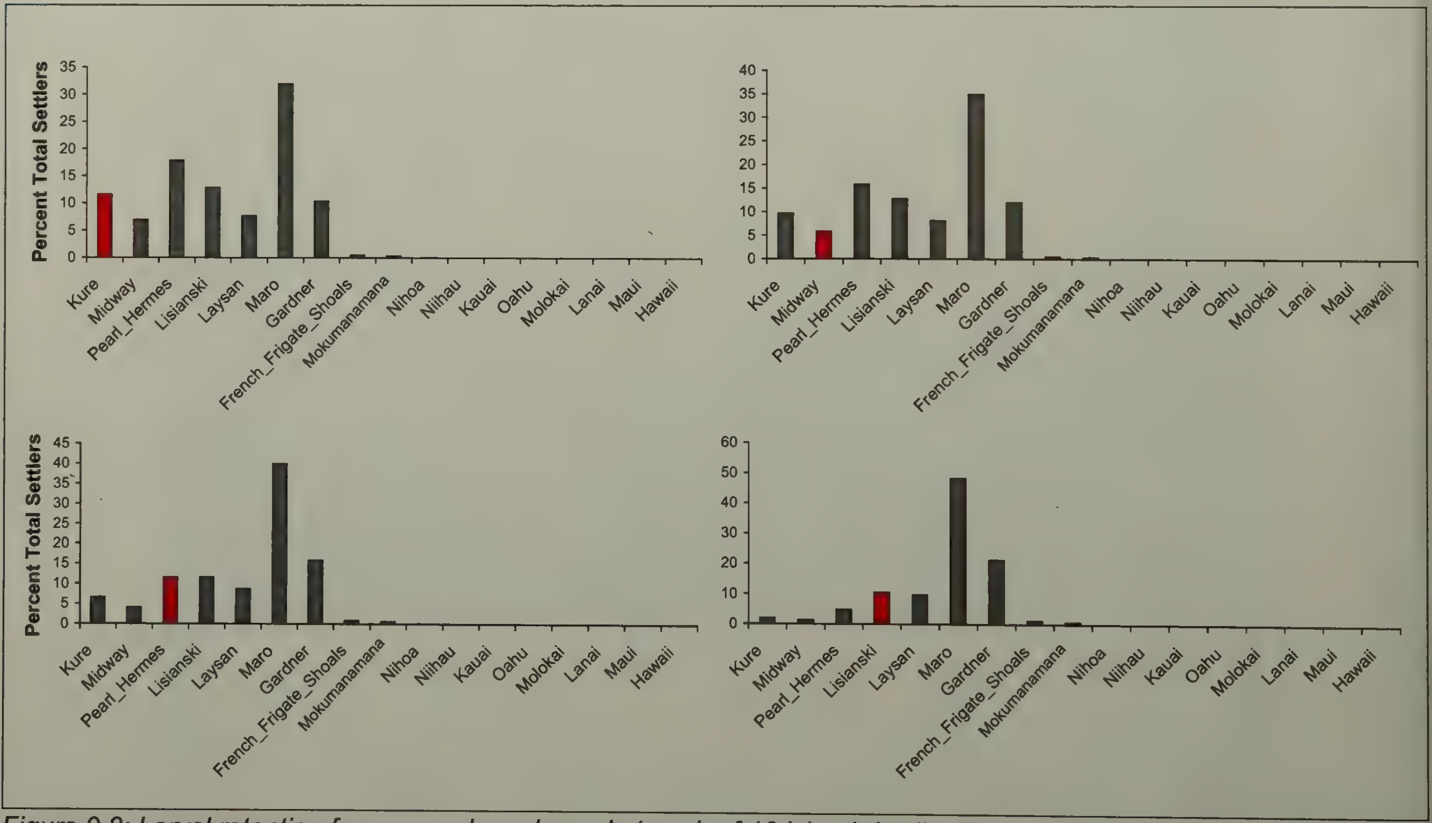


Figure 9.8: Larval retention for propagules released at each of 10 islands/atolls. The red bars in each graph indicate the island or atoll from which the larval propagules were initially released. Source: Kobayashi, unpublished data.

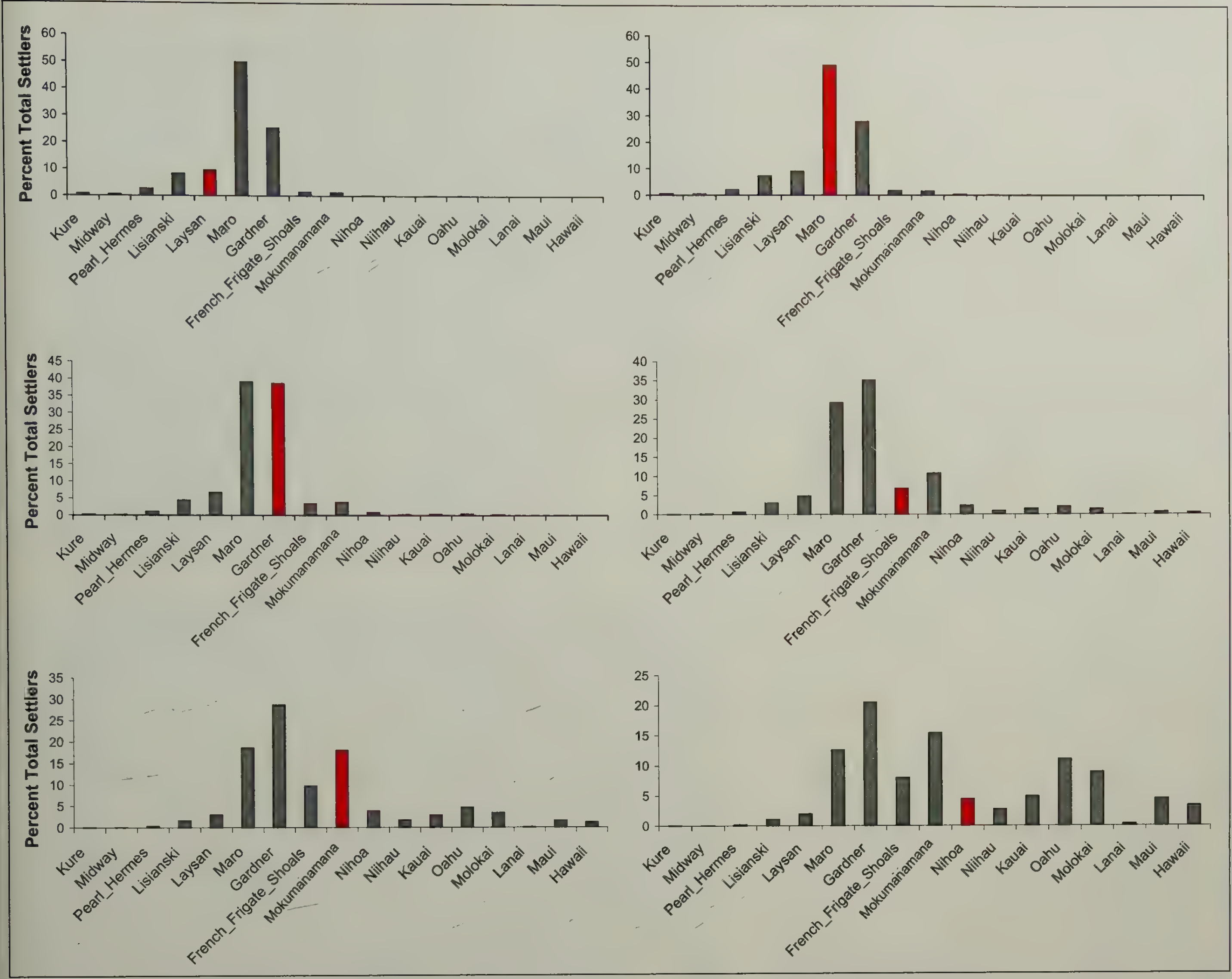


Figure 9.8 (continued): Larval retention for propagules released at each of 10 islands/atolls. The red bars in each graph indicate the island or atoll from which the larval propagules were initially released. Source: Kobayashi, unpublished data.

Directed Movements of Adult Fishes– Connectivity at the Scale of the Individual

Acoustic telemetry of giant trevally (white ulua, *Caranx ignobilis;* Figure 9.9) and jobfish (uku, *Aprion virescens;* Figure 9.9), large-bodied apex predators on Hawaiian reefs, revealed each to be site attached and home ranging (Meyer et al., 2007a,b; Figure 9.10). No inter-atoll movements were detected but animals were site attached to core activity areas where they exhibited diel habitat shifts and made periodic atoll-wide excursions up to 29 km. Movements to seasonal mating aggregations were identified in the summer during specific phases of the moon for each species.

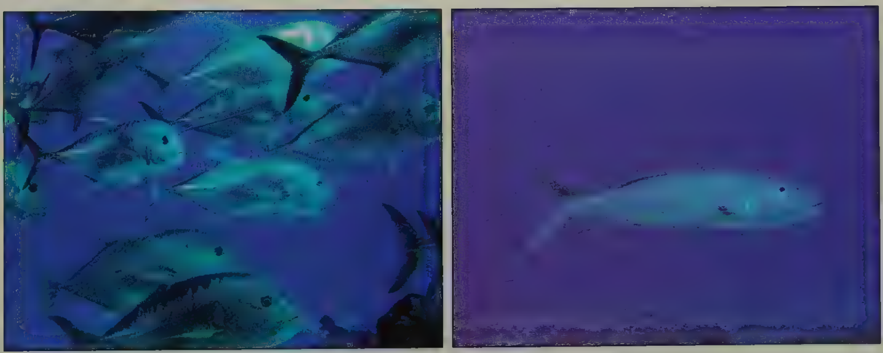


Figure 9.9. Giant trevally (left) and jobfish (right) are both large, top predators in the NWHI coral reef ecosystem. Photos: J. Zamaow and J. Maragos.

Giant Trevally Movement

A large proportion of giant trevally from French Frigate Shoals were caught at La Perouse Pinnacle, and these fish all showed high detections/day at this location, verifying their strong site fidelity to a core area (Figures 9.11). The lower detection/day at East and Tern Islands also suggests that these locations are on the periphery of the fish's home range (none of the fish detected at East or Tern were tagged at those locations). The large number of fish detected at Rapture Reef suggests this site provides important habitat for giant trevally at French Frigate Shoals, as fish tagged throughout the atoll made seasonal excursions to this reef. The arrival and departure times of fish were strongly correlated with each other and in turn with the lunar cycle. Coupled with anecdotal diver observations, the acoustic data indicate that Rapture Reef is likely a spawning aggregation site for giant trevally at French Frigate Shoals. Giant trevally tagged at Rapture Reef were detected there year round, suggesting that their core home range was located within the spawning habitat. These fish did not make long seasonal movements, as their core ranges were within the spawning area. The seasonal spawning behavior of giant trevally was characterized by daily runs to the spawning locations during the lunar spawning cycle. They did not shift their core home range to the spawning location, as they returned to their core range (e.g., La Perouse) after each spawning event.

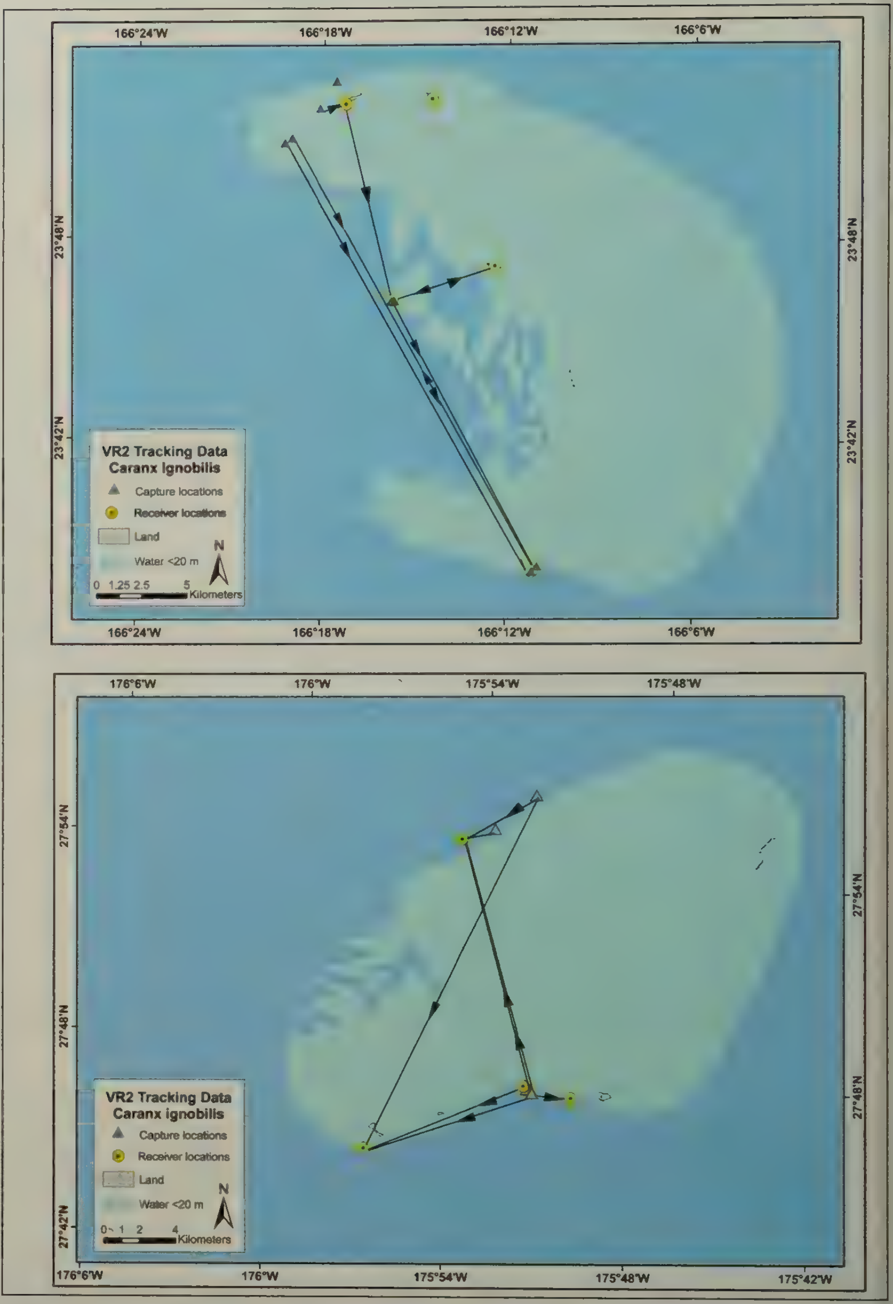


Figure 9.10. Trans-atoll movements of giant trevally at French Frigate Shoals (top) and Pearl and Hermes (bottom; Meyer et al., 2007a). Circles indicate locations of VR2 receivers, shaded squares indicate giant trevally capture sites (numbers within square symbols indicate sites where multiple individuals were tagged and released). Lines with arrows indicate most direct route between giant trevally release and detection locations.

At Pearl and Hermes Atoll, the greatest number of detections of tagged giant trevally (for each individual fish) occurred at the receiver closest to the location where the fish was originally tagged, providing evidence that they show strong site fidelity to core areas (Figure 9.12). Giant trevally were detected at receivers at other parts of the atoll, suggesting that these areas were on the periphery of the fish's home range. These were most likely areas visited during the diel habitat shifts exhibited by almost all individuals. Fish tagged at the Main Channel showed greater detections/day at large at the Main Channel receiver, compared to receivers close to fish tagged at other parts of the atoll (e.g., northwest corner). The Main Channel is shallow and experiences very strong, tidally-driven currents. These strong currents bring animals and materials in and out of the lagoons, which appears to make the Main Channel a desirable habitat for apex predators, as suggested by the large number of large sharks and teleosts seen at this location.

Only a limited number of giant trevally were tagged at Midway and Kure Atolls, resulting in few detections and no evidence of movement (Figures 9.13 and 9.14). Shallow flats appear to be poor habitat for this species, as all receivers located in shallow flats at various atolls recorded very few detections.

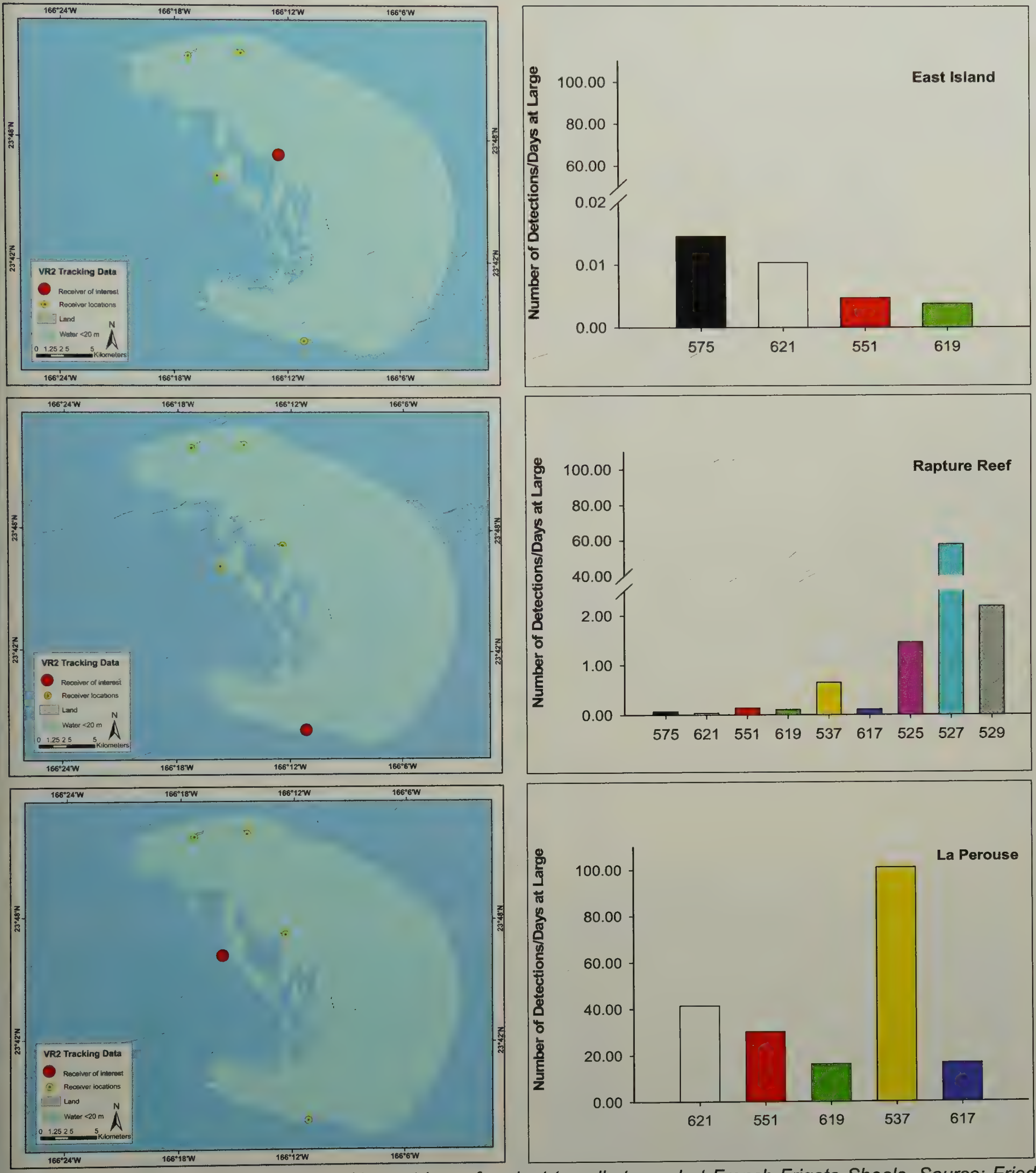


Figure 9.11. Number of tag detections/days at large for giant trevally tagged at French Frigate Shoals. Source: Friedlander, unpub. data; maps: L. Wedding.

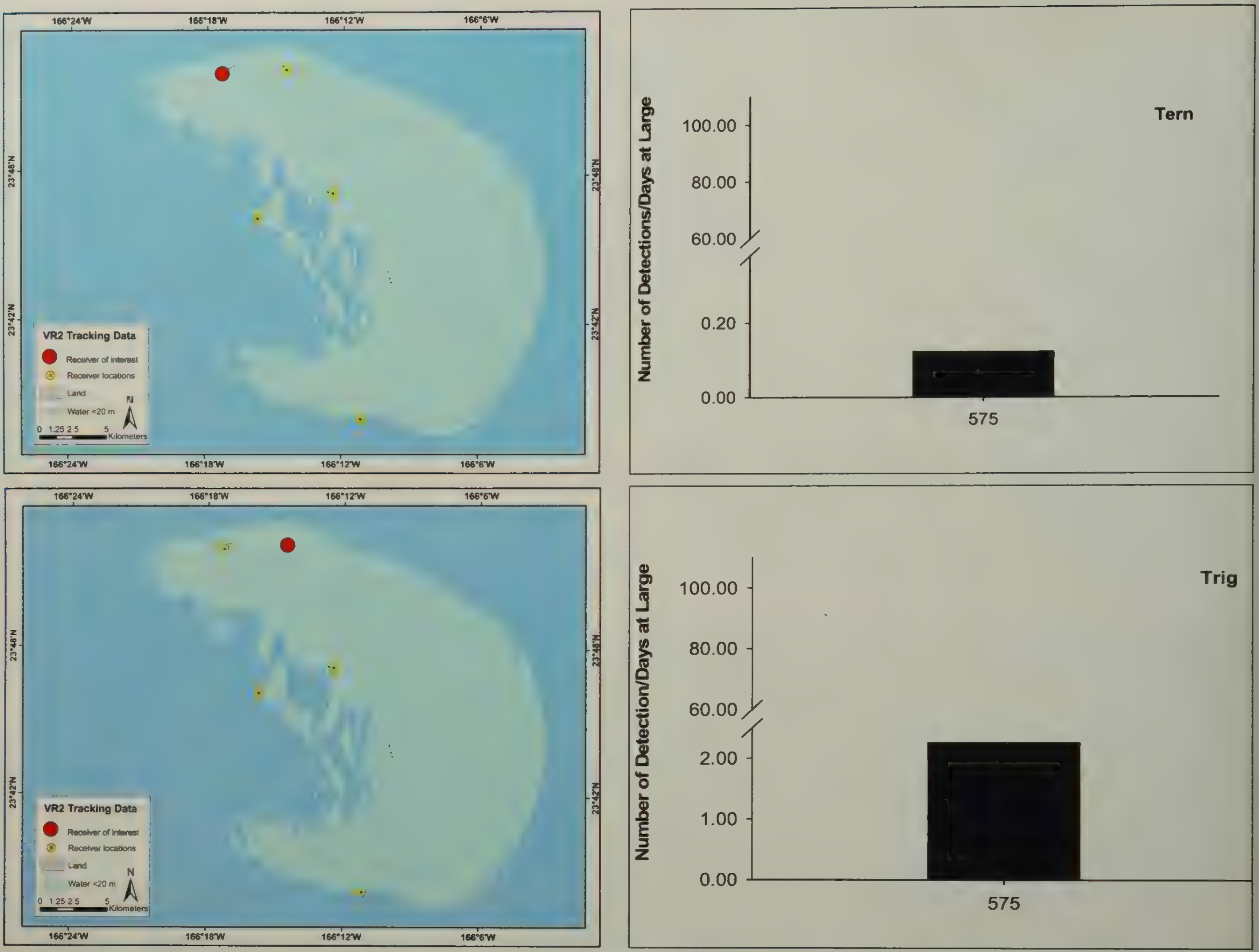


Figure 9.11 (continued). Number of tag detections/days at large for giant trevally tagged at French Frigate Shoals. Source: Friedlander, unpub. data; maps: L. Wedding.

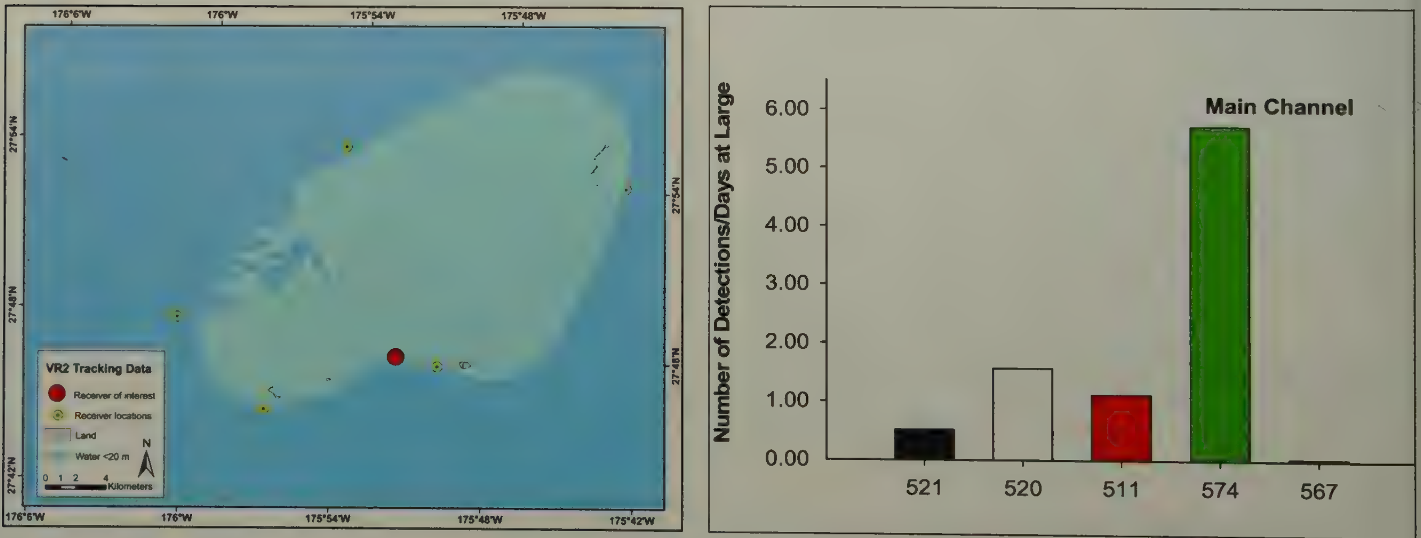


Figure 9.12. Number of tag detections/days at large for giant trevally tagged at Pearl and Hermes Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

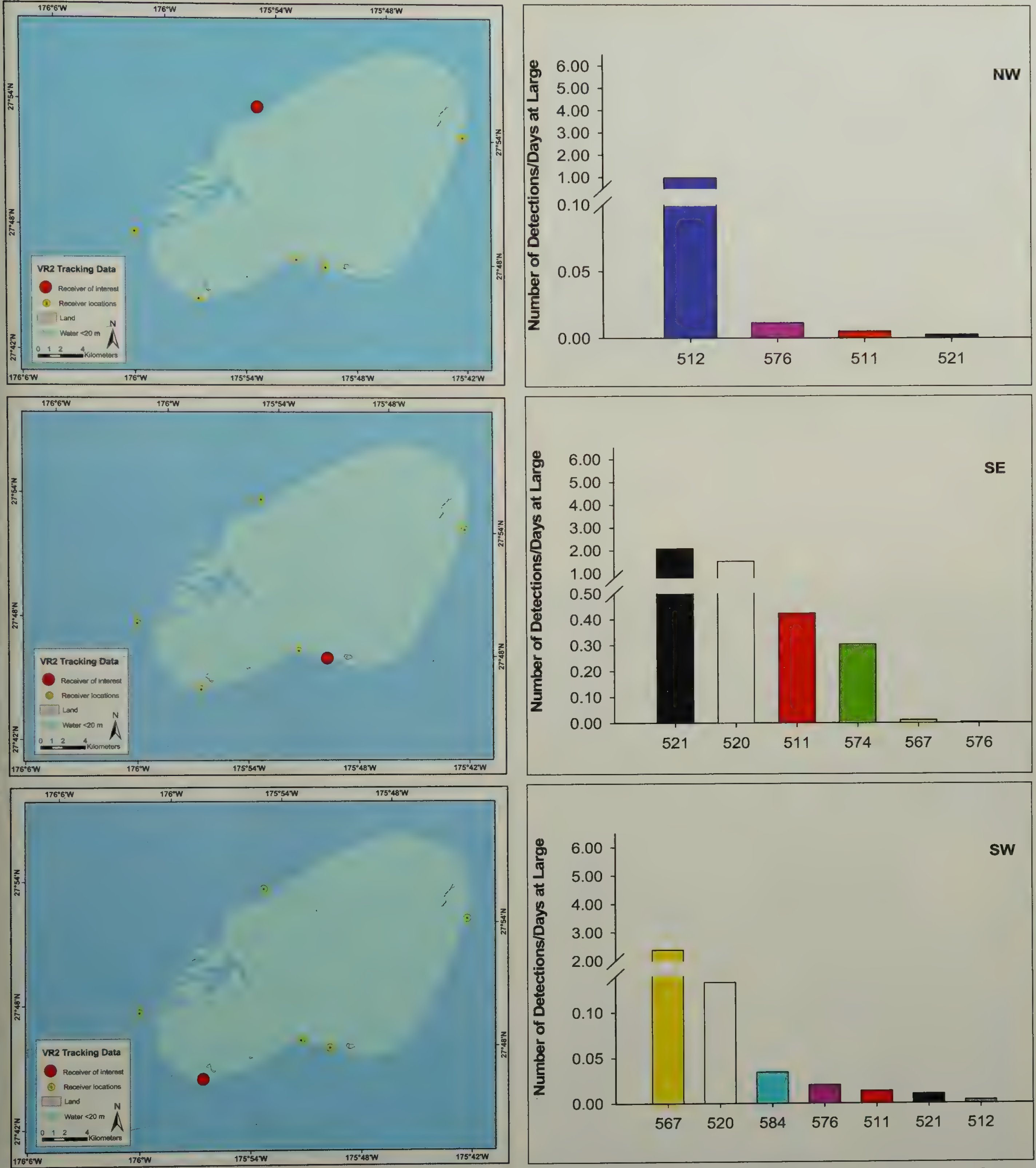


Figure 9.12 (continued). Number of tag detections/days at large for giant trevally tagged at Pearl and Hermes. Source: Friedlander, unpub. data; maps: L. Wedding.

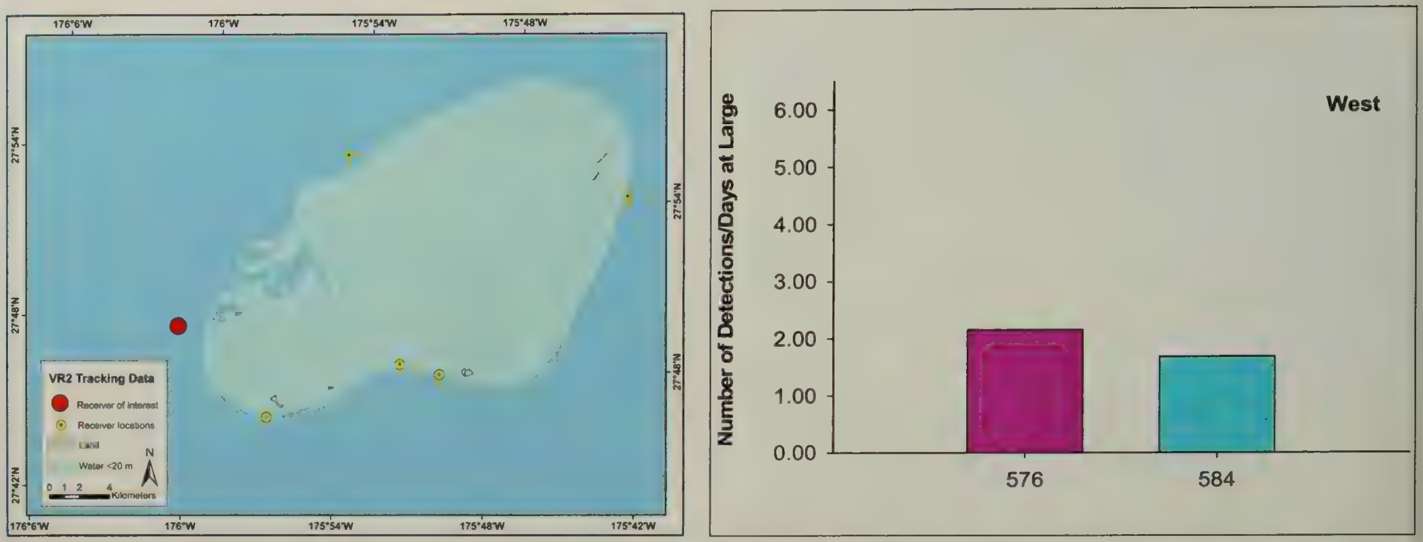


Figure 9.12 (continued). Number of tag detections/days at large for giant trevally tagged at Pearl and Hermes Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

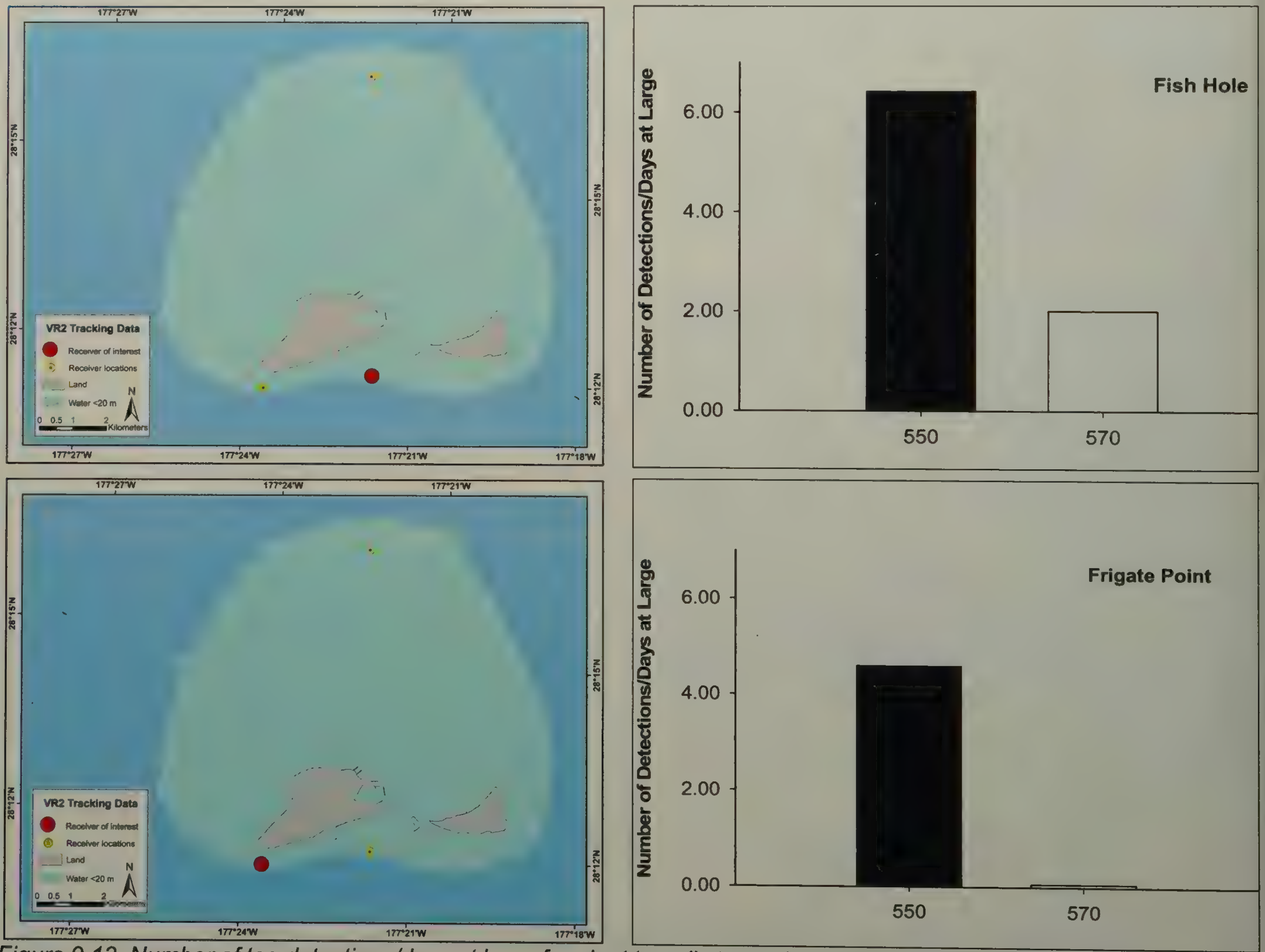


Figure 9.13. Number of tag detections/days at large for giant trevally tagged at Midway Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

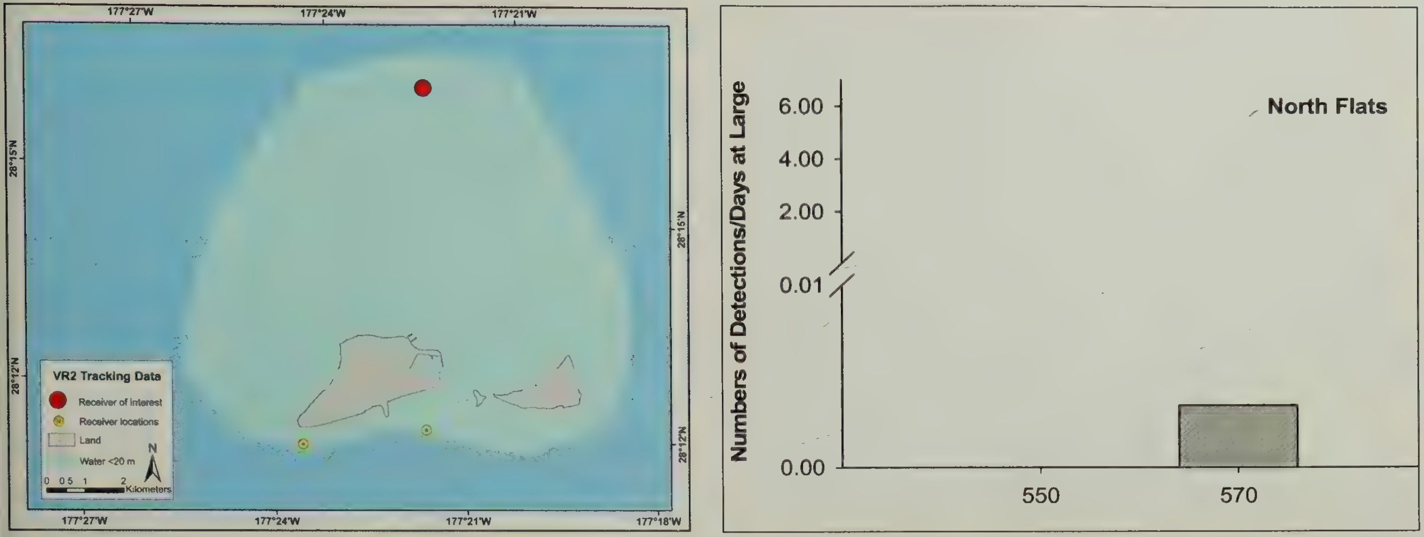


Figure 9.13(continued). Number of tag detections/days at large for giant trevally tagged at Midway Atoll. Friedlander, unpub. data; maps: L. Wedding.

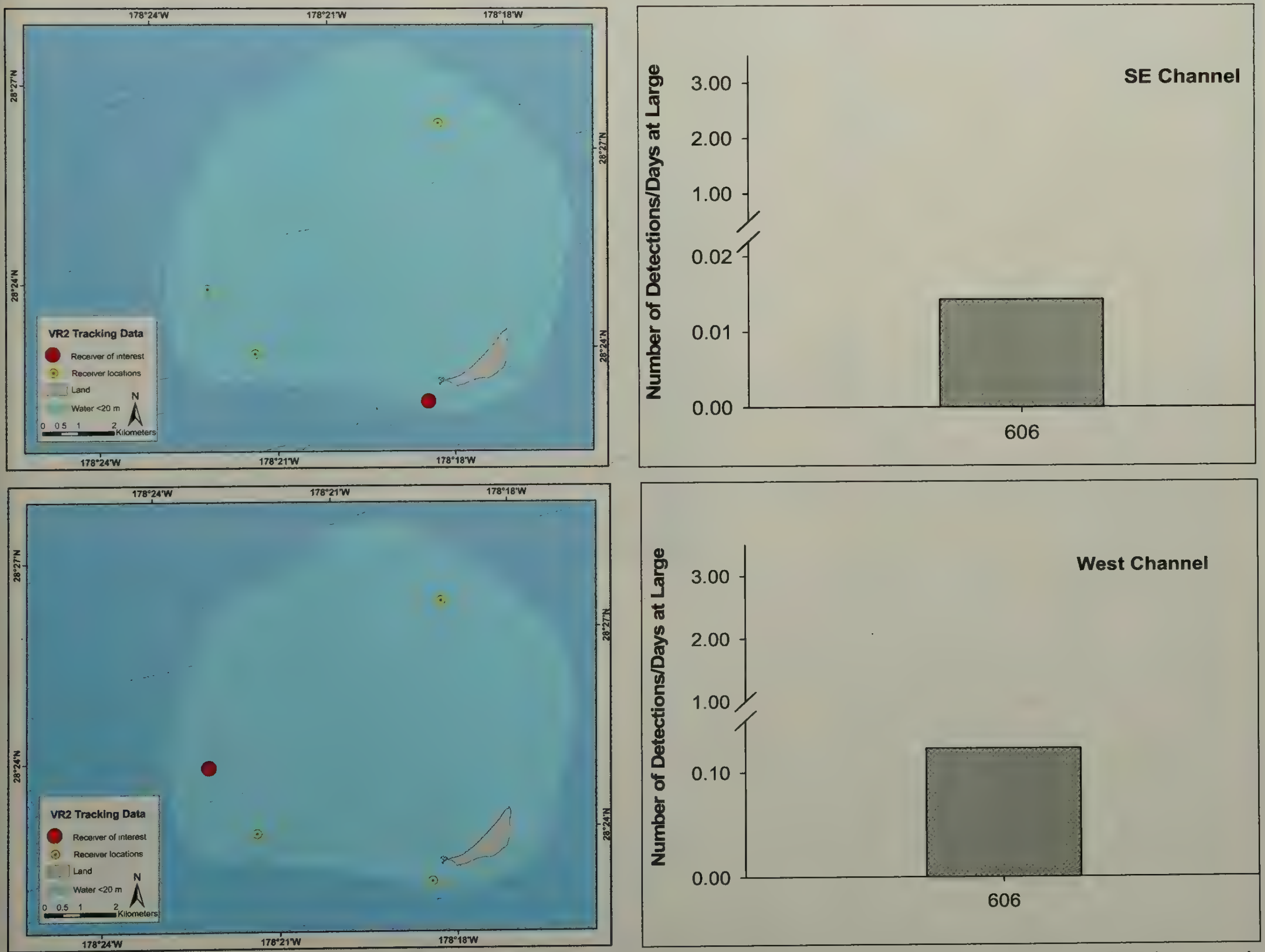


Figure 9.14. Number of tag detections/days at large for giant trevally tagged at Kure Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

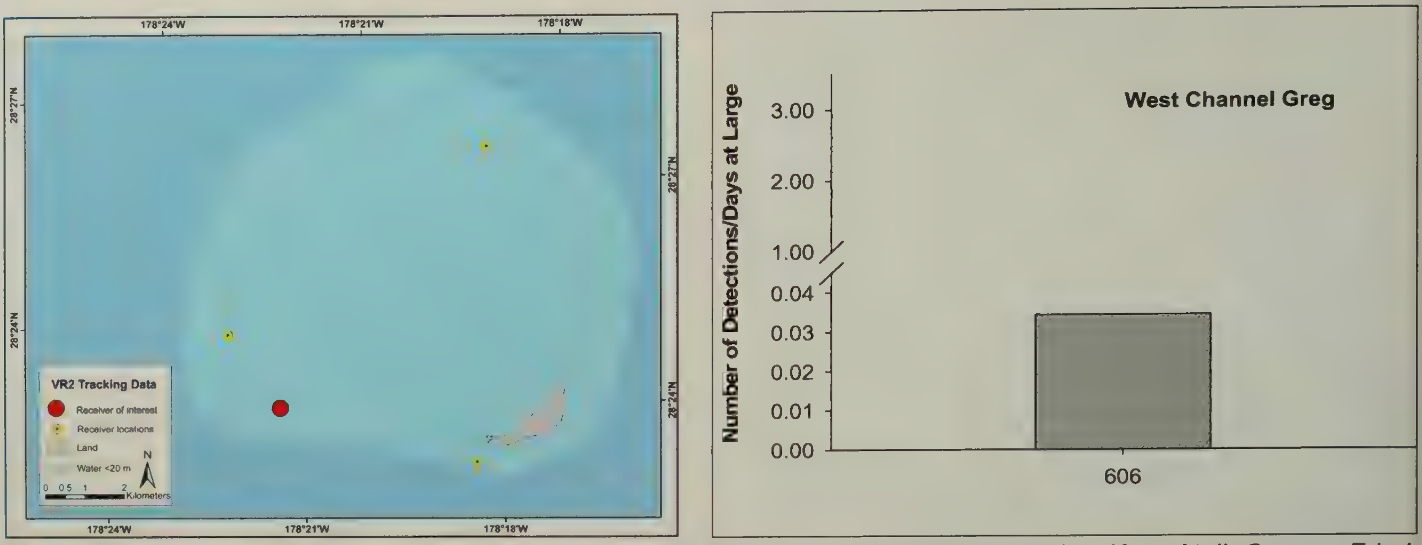


Figure 9.14 (continued). Number of tag detections/days at large for giant trevally tagged at Kure Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

Jobfish Movement

Movement patterns for jobfish were similar to those observed for giant trevally (Figures 9.15). For example, all fish detected at Rapture Reef were tagged at Disappearing Island, located close to Rapture Reef (Figure 9.16). However, there was no evidence that Rapture Reef is a spawning location for jobfish. Jobfish tagged along the south coast of Pearl and Hermes Atoll were detected by receivers on both the southwest and southeast tips (Figure 9.17). This suggests behavior associated with long, daily and tidal excursions.

Overall, jobfish had lower numbers of detections/day than giant trevally. This may be a function of a key difference in their spawning strategy, as well as a tendency for greater diel movement. Unlike giant trevally, jobfish perform complete seasonal shifts in their home range, occupying separate summer and winter core areas. These winter and summer locations do not overlap, which is why each receiver generally has fewer detections on an annual basis. However, jobfish were occasionally detected in their winter or summer location during the opposing season, suggesting that these seasonal core areas are relatively close to each other.

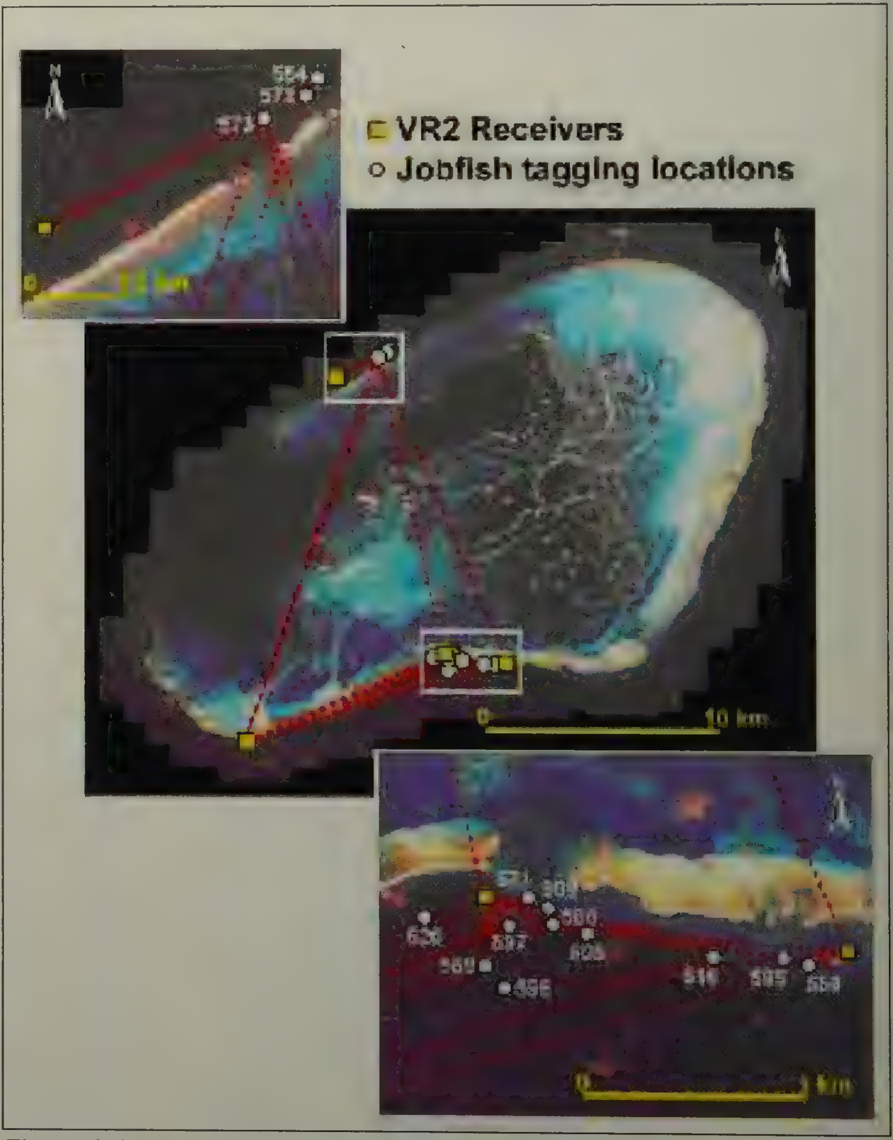


Figure 9.15. Trans-atoll movements of jobfish at Pearl and Hermes Reef with enlarged views of capture areas (insets) showing VR2 receiver locations (yellow squares), jobfish capture sites (white circles), jobfish transmitter codes (white numbers), most direct routes between jobfish release and detection locations (dashed red lines). Source: Meyer et al., 2007b.

Jobfish at Kure atoll also show strong site fidelity to core areas, and fish have been detected at one receiver for over three years. Again, however, diel and tidal movements result in jobfish moving over a large area, as exemplified by the different detection patterns for individual fish seen in Figures 9.18 and 9.19. These fish make complete seasonal shifts in habitat as can be seen by the absence of detections during either the summer or winter months. The fact that fish were detected, fish that were absent either during the summer or the winter months, suggests that the spawning habitats for this species were located at Kure, and that there is more than one spawning location at the atoll.

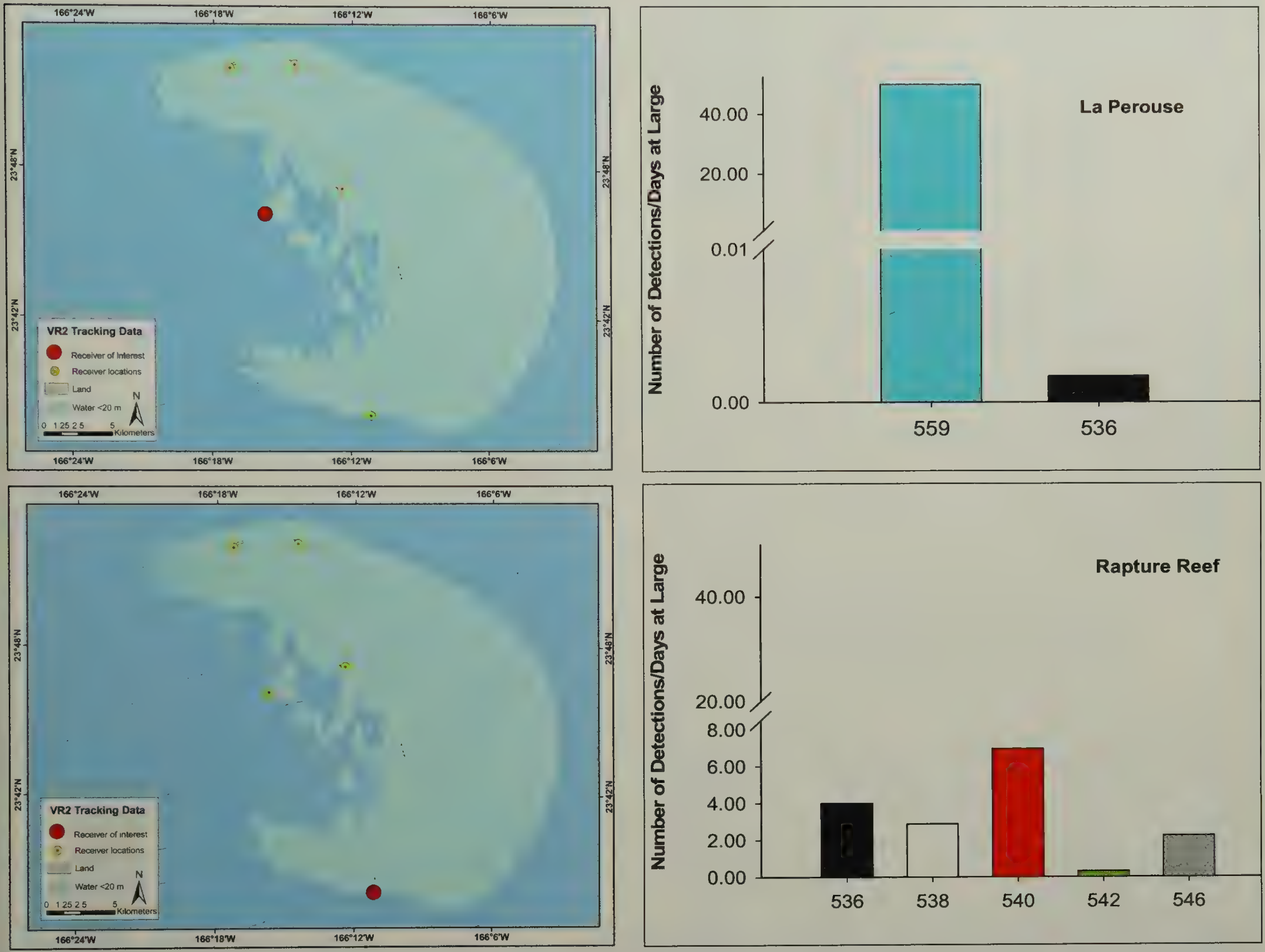


Figure 9.16. Number of tag detections/days at large for jobfish tagged at French Frigate Shoals. Source: Friedlander, unpub. data; maps: L. Wedding.

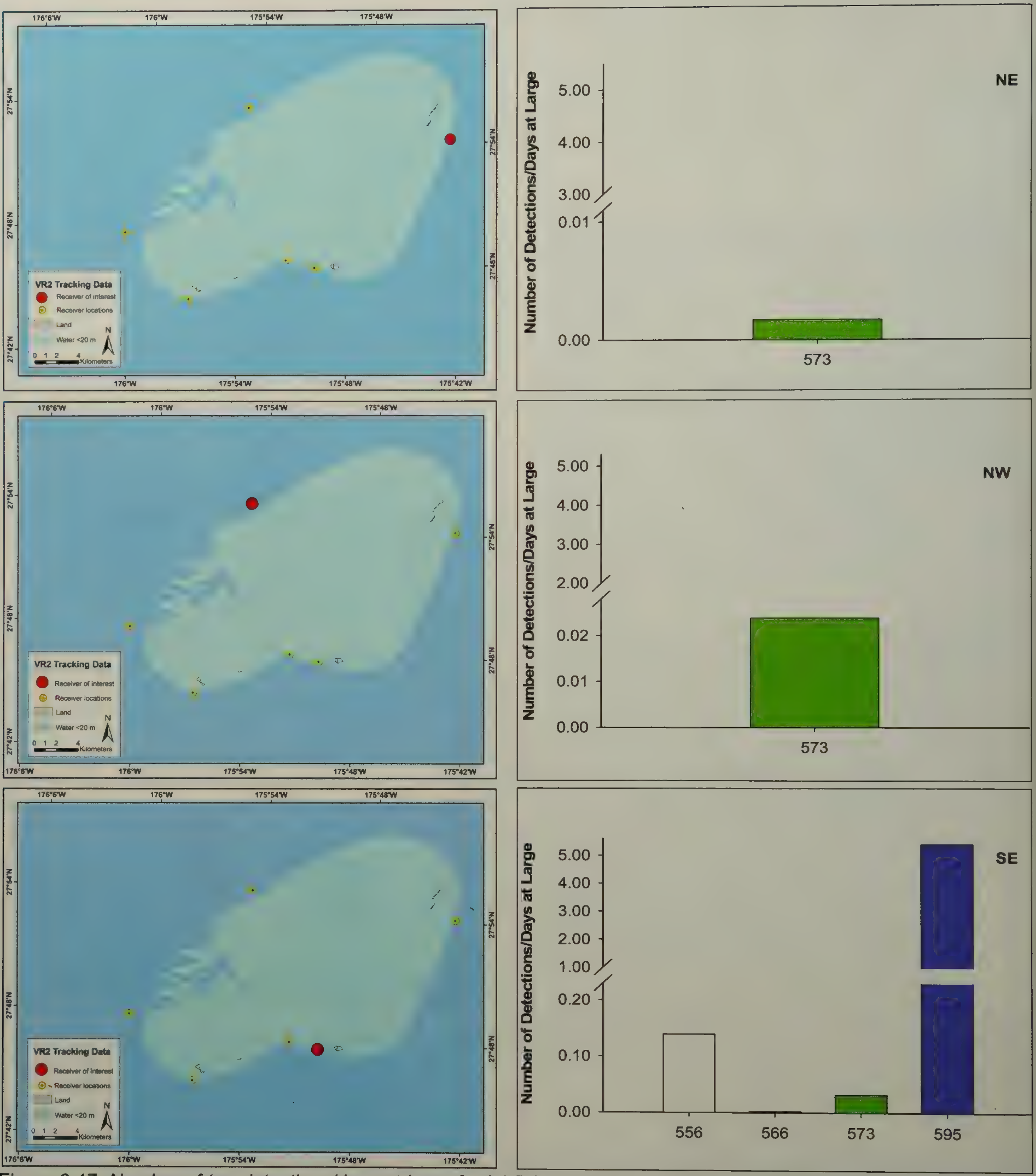


Figure 9.17. Number of tag detections/days at large for jobfish tagged at Pearl and Hermes Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

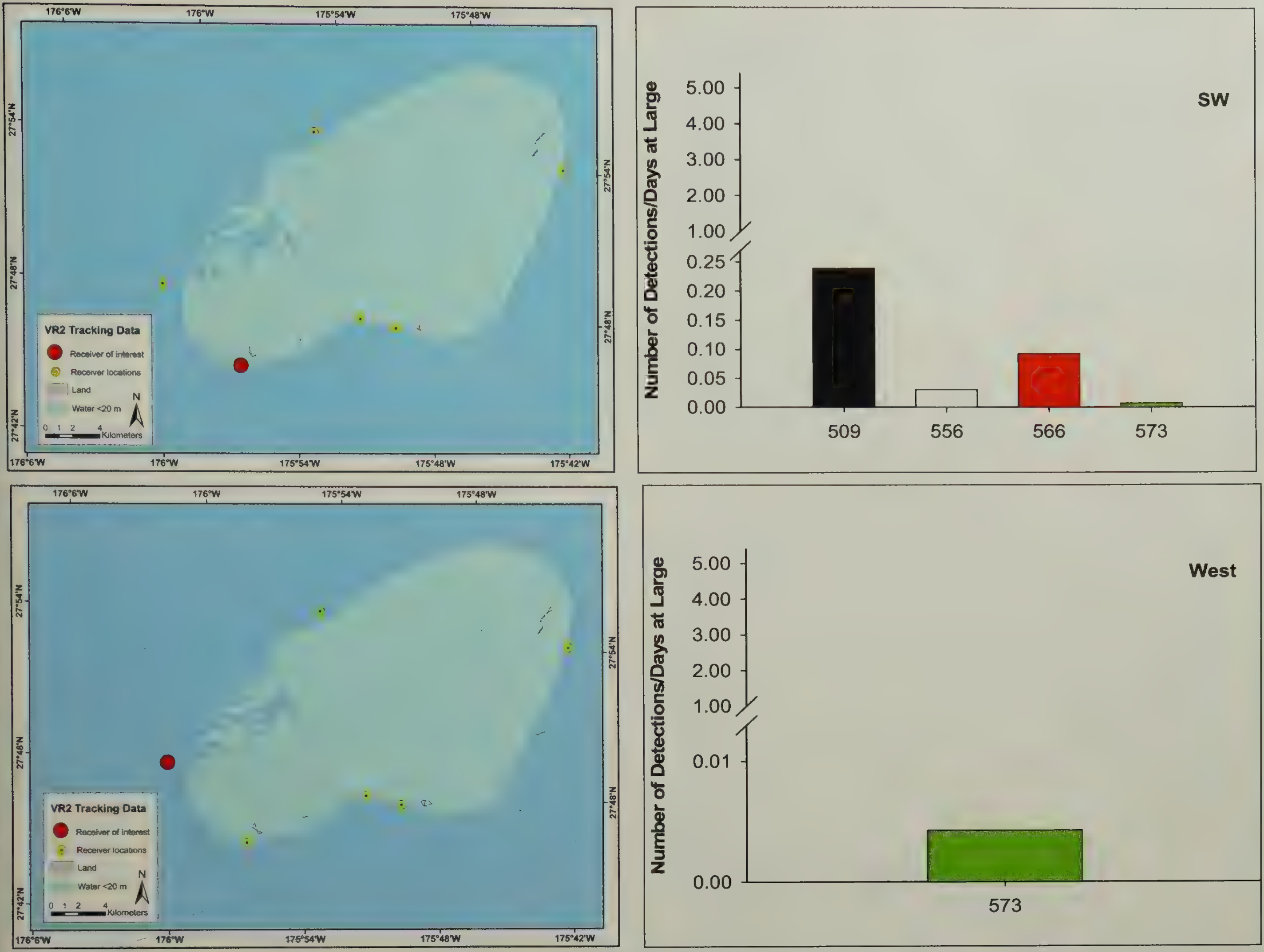


Figure 9.17 (continued). Number of tag detections/days at large for jobfish tagged at Pearl and Hermes Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

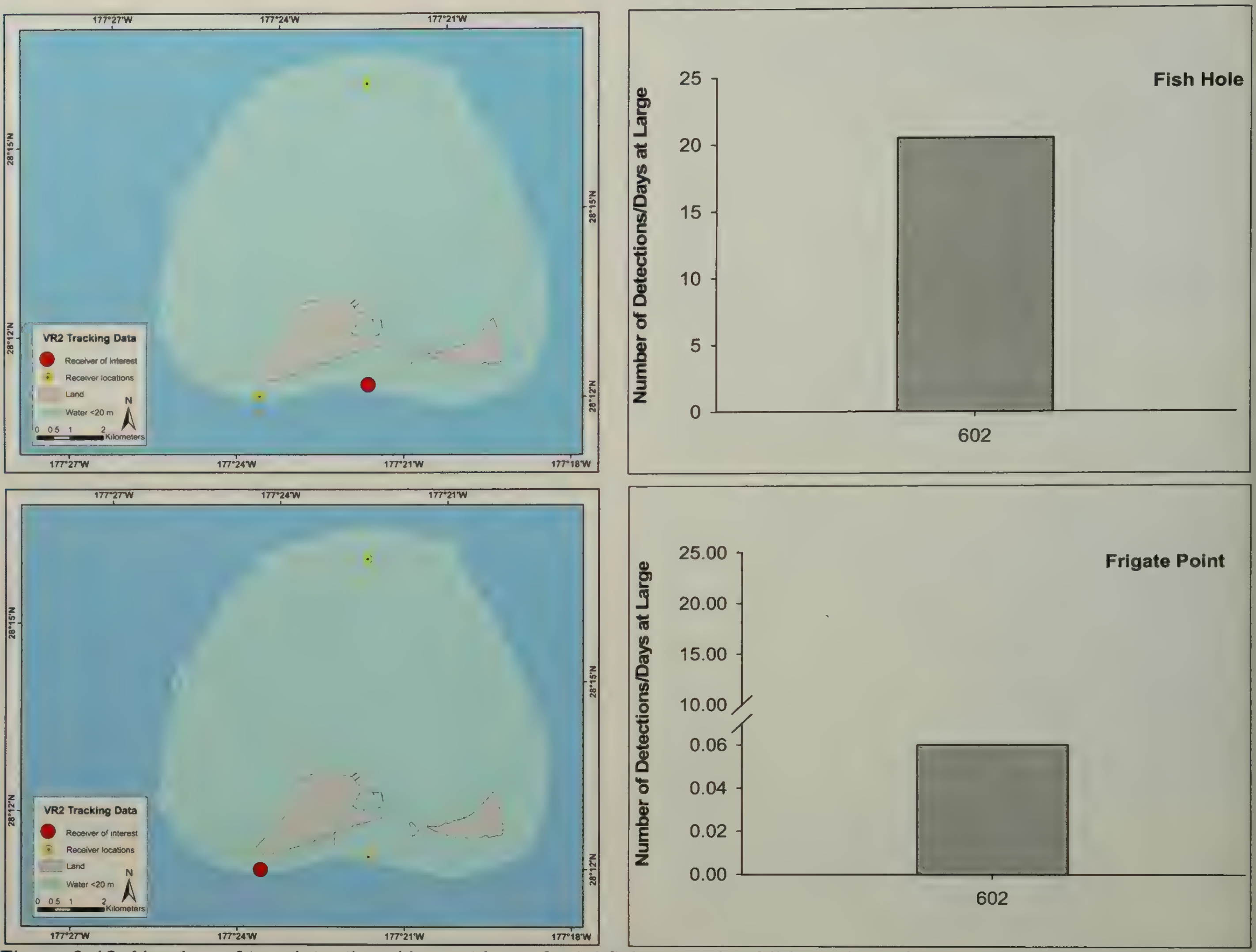


Figure 9.18. Number of tag detections/days at large for jobfish tagged at Midway Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

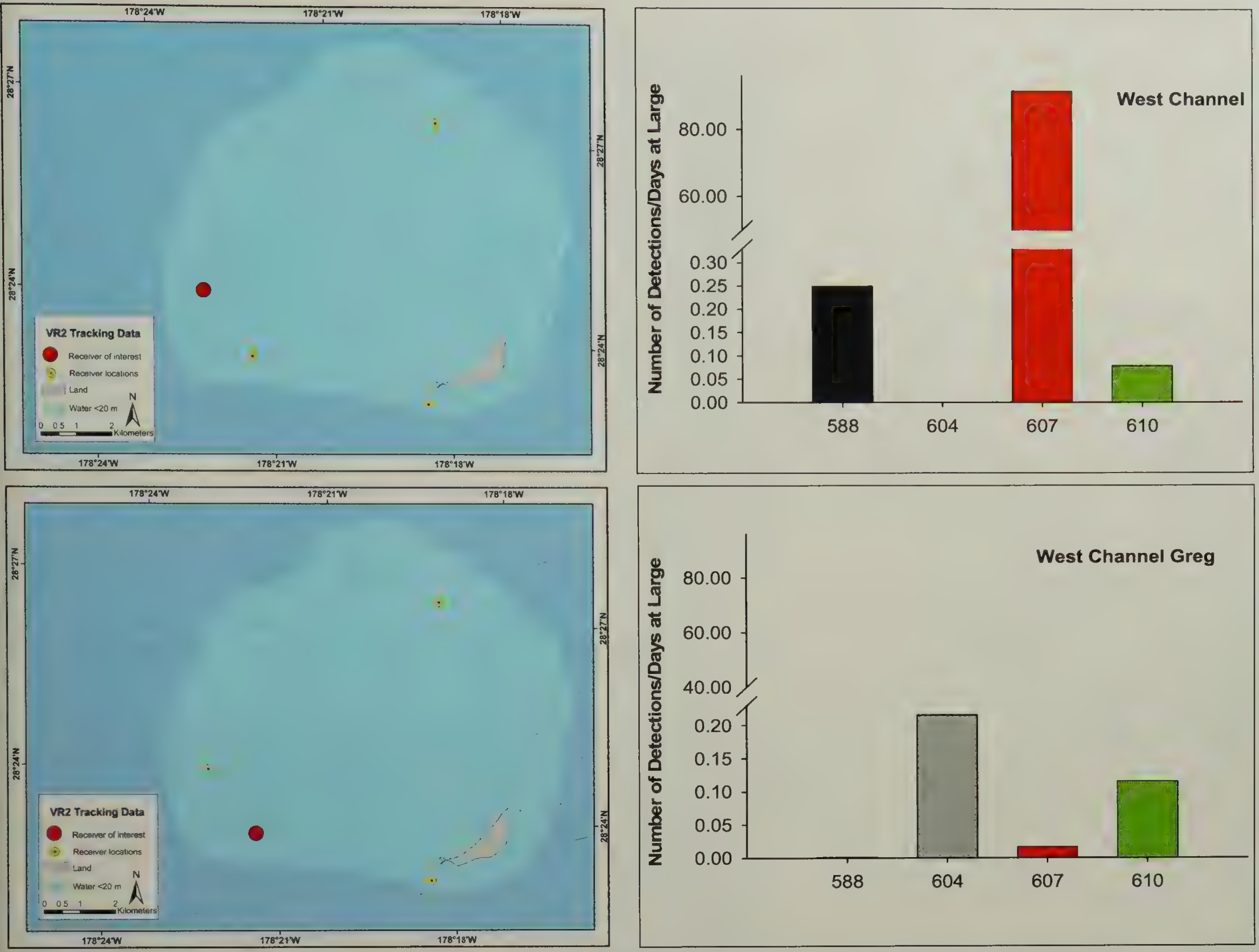


Figure 9.19. Number of tag detections/days at large for jobfish tagged at Kure Atoll. Source: Friedlander, unpub. data; maps: L. Wedding.

Inferring Dispersal and Movement by Tracking Introduced Species

Eleven species of shallow-water snappers (F. Lutjanidae) and groupers (F. Serranidae) were purposely introduced to one or more of the main (high) islands of the Hawaiian Archipelago in the late 1950s and early 1960s. Of these, three snapper species and one grouper have become established (Randall, 1987). One snapper, blueline snapper (Taape or *Lutjanus kasmira*), and one grouper, Peacock grouper (Roi or Cephalopholis argus), are well-established, and have histories of colonization along the island chain that are reasonably well-documented. Planktonic stage durations, although unknown for both species, are grossly estimable based on congeners elsewhere in the Indo-Pacific. These two species thus represent a unique opportunity to track the rate of colonization of introduced species within an oceanic insular ("stepping stone") environment.

Blueline snapper, if like several other Indo-Pacific congeners, has a planktonic stage duration approximating 25-47 days and a settlement size greater than 20-30 mm (Leis, 1987), but there is a great deal of geographic, seasonal, and other environmental variations in stage duration within and among closely related species (Leis,1993; Victor, 1993). Given these same caveats, Peacock grouper, if a typical member of its genus in the subfamily Epinephelinae, settles at a size of about 18 mm (Leis, 1987) and is likely to have a shorter pelagic larval stage than blueline snapper.

A total of about 3,170 blueline snapper were introduced from the Marquesas Islands to Hawaii beginning in 1955, including 2,435 released in Kaneohe Bay, Oahu, in 1958 (Oda and Parrish, 1981; Randall, 1987; Figure 9.20). The species had colonized the Big Island of Hawaii, 140 nmi downchain of Oahu, by 1960 (Randall,1987). Blueline snapper had spread upchain to French Frigate Shoals in the NWHI, 490 nmi from

Oahu, by sometime between 1977 and 1982 (Okamoto and Kanenaka, 1984). The species was sighted another 330 nmi farther upchain in the NWHI at Laysan Island (820 nmi from Oahu) in June 1979 (Parrish et al., 1980; Oda and Parrish, 1981). A few individuals were first observed at Midway Atoll, 240 nmi farther upchain from Laysan island (1,180 nmi from Oahu), in May-June 1992; the species had not been observed on similar surveys conducted at Midway in 1989 and 1991 (Randall et al., 1993). These records suggest rates of dispersal of about 18-70 nmi/year for blueline snapper subsequent to its introduction to Hawaiian waters. This is consistent with estimates of realized mean dispersal distance ranging from 33 to 130 km/year from Shanks et al. (2003).

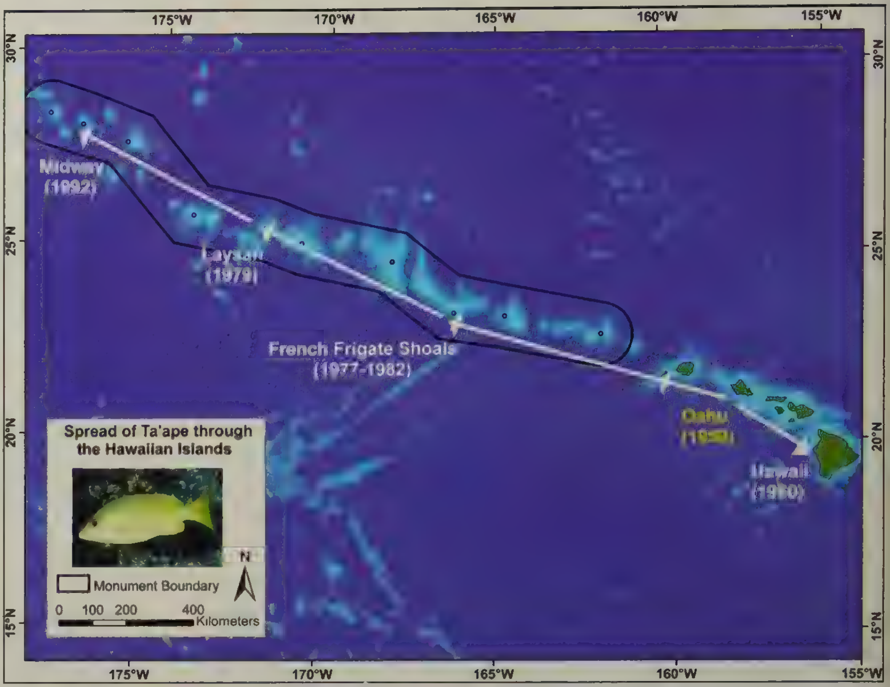


Figure 9.20. Spread of the introduced blueline snapper (Taape, Lutjanus kasmira*) throughout the Hawaiian Islands. Source: Sladek Nowlis and Friedlander, 2004.*

The dispersal of Peacock grouper following its introduction to Hawaii is not as well documented. However it is clear that Peacock grouper has spread less extensively than blueline snapper over approximately the same time period (Figure 9.21). In 1956, a total of 571 *C. argus* were introduced from Moorea in French Polynesia to Oahu (n=171) and to the Kona coast of the Big Island (n=400; Randall, 1987). At present, it has been documented as far upchain as Niihau, 120 nmi from Oahu, where it was first observed in November 1978 (Hobson, 1980). No shallow reef fish surveys of the westernmost MHI were conducted prior to this time. Peacock grouper was absent at French Frigate Shoals in 1992 and has been mostly absent in annual surveys conducted there between 1995 and 2003 (E. DeMartini, unpubl. data). Based on this meager data, a dispersal rate of >5 nmi per year is suggested. Although pelagic duration estimates are approximate, Peacock grouper-- the species with a likely shorter-duration pelagic stage-- has spread much more slowly through the Hawaiian Archipelago than blueline snapper. Blueline snapper clearly belongs to the long-distance dispersal group (mode greater than 16 km/year); Peacock grouper probably belongs to this group as well, albeit closer to the lower bound.

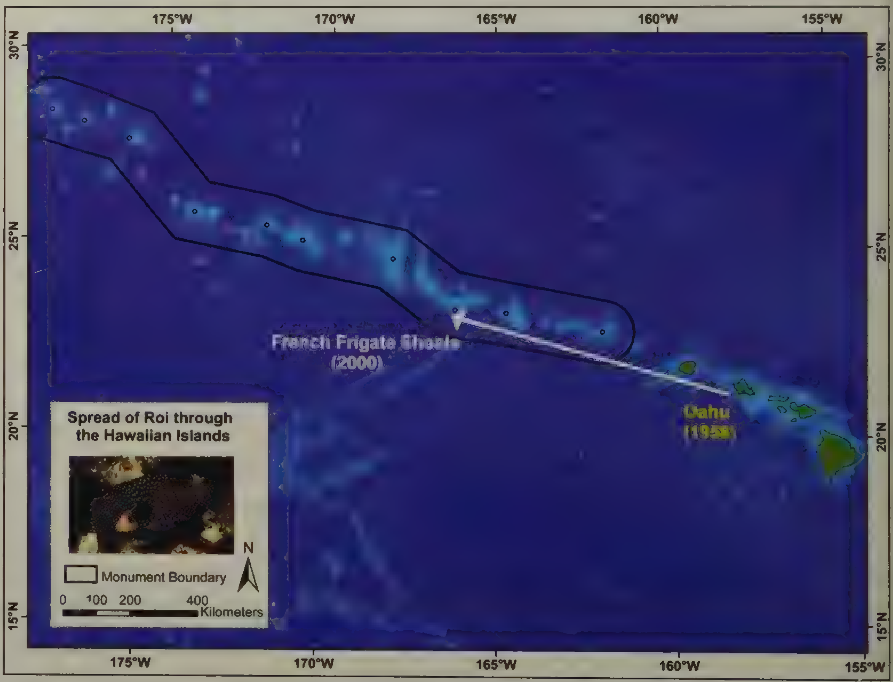


Figure 9.21. Spread of the introduced Peacock grouper (Roi, Cephalopholis argus*) throughout the Hawaiian Islands. Source: Sladek Nowlis and Friedlander, 2004.*

Genetic Connectivity Studies

Ongoing research will determine genetic dispersal among islands and atolls of the NWHI, including both invertebrates and reef fishes, using molecular genetic markers to resolve populations and evolutionary partitions. Preliminary results indicate large differences among taxa in their degree of connectivity throughout the archipelago. Some species appear to move around the archipelago with relative ease and show no significant population structure in the NWHI and MHI (e.g., reef fish; Schultz et al., 2007; Craig et al., 2007). Other species show modest but significant population structure, including the endemic grouper (Rivera et al., 2004), spinner dolphins (Andrews et al., 2006) and two damselfishes (Ramon et al., 2008).

Opihi, the Hawaiian endemic limpets (*Cellana exarata*; *C. sandwicensis*, Figure 9.22; and *C. talcosa*), show striking population differentiation between the MHI and NWHI (Bird et al., 2007). All three species of opihi show significant differentiation of populations across the Hawaiian Archipelago, but the spatial scales, patterns and magnitudes of partitioning differ by almost an order of magnitude among species. Preliminary data from hermit crabs (Baums et al., in prep) indicate variable connectivity in this group as well. There is significant population differentiation between the MHI and NWHI for all three species of opihi, and estimates of dispersal (migrants per generation ≤3) are so low that recruitment from the NWHI would likely have negligible impact on depleted MHI populations. Even within the MHI, the koele (*C. talcosa*) exhibits such strong population differentiation that if the Kauai population were depleted, it could not recover within our lifetime (Bird et al., 2007).

*Figure 9.22. A yellowfoot opihi (*Cellana sandwicensis*) at Kauai. All Hawaiian* Cellana *spp. are endemic to the archipelago and exhibit a striking population differentiation between the main and northwestern islands. Photo: C.E. Bird.*

Kobayashi (2006) recently used a computer simulation to infer patterns of larval dispersal between Johnston Atoll and the Hawaiian Archipelago. Results indicate a "northern corridor" which connects Johnston Atoll and the central portion of the NWHI and a "southern corridor" which connects Johnson Atoll to the MHI. Sampling was conducted at Johnston Atoll in 2006 to assess connectivity between the NWHI and this isolated reef habitat. The sea cucumber *Holothuria atra* exhibited low connectivity between Oahu and French Frigate Shoals and between Oahu and Johnston (Skillings et al., in prep; Figure 9.23). In contrast, there was no significant difference between samples from French Frigate Shoals and Johnston, supporting the northern corridor for dispersal between Johnston and the Hawaiian Archipelago (Figure 9.23). This result

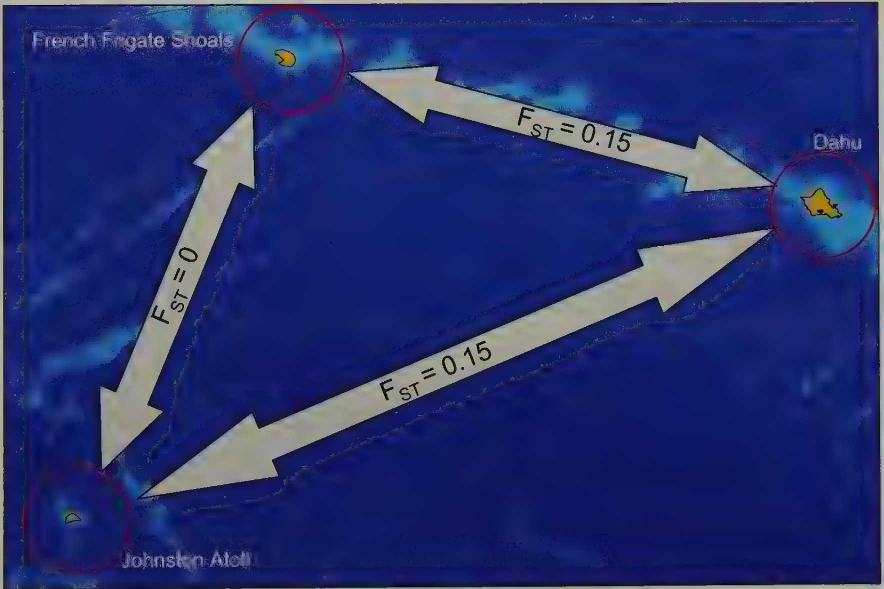


Figure 9.23. F-statistics demonstrate population genetic separations for the sea cucumber Holothuria atra *between Oahu (MHI) and French Frigate Shoals (NWHI), and between the MHI and Johnston, but high connectivity between Johnston and French Frigate Shoals. Source: Skilling et al., in prep.*

supports the hypothesis first advanced by Grigg (1981) and Maragos and Jokiel (1986) that Johnston is a potential gateway that enhances biodiversity in the NWHI. However the alternative hypothesis, that Johnston is an outpost of the Hawaiian fauna, remains a viable possibility pending further research.

Results thus far indicate that population structure across the Hawaiian archipelago does not fit a simple isolation-by-distance model, and generalizations based on average (geostrophic) oceanographic currents may not be warranted (Figures 9.24). Closely-related species with similar ecology and reproductive biology (including opihi, hermit crabs, and reef fishes) can have dramatically different patterns of connectivity (Bird et al., 2007; Rocha et al., 2007). Together, these results mandate that a suite of invertebrates and fish must be surveyed to resolve general trends, and to provide connectivity information pertinent to management of the PMNM.

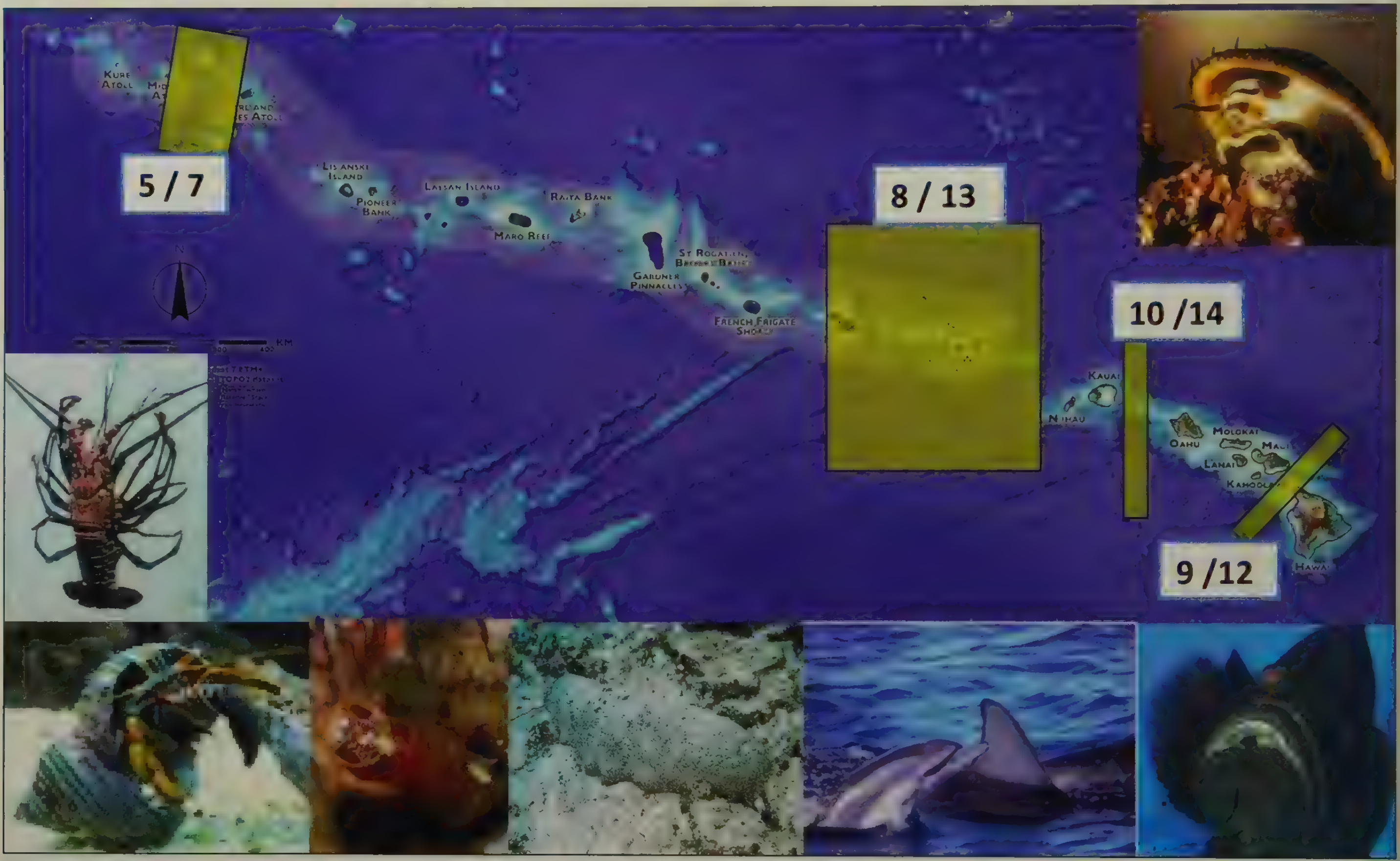


Figure 9.24. Apparent shared barrier to dispersal in the Hawaiian Archipelago. Consensus of significant genetic partitions among up to 14 marine species across the Hawaiian Archipelago. Locations of apparent restrictions to dispersal are marked with yellow bands, and the number of species that share that break out of the total number of species surveyed for each location are also given. These results are preliminary, but the shared genetic structure among highly divergent species thus far is striking.

Connectivity considerations are particularly important for Hawaiian endemic species. Conservation of Hawaiian endemic species should take into account the consequences of their restricted distribution, including reduced capacity for recovery following depletion. Recently, scientists at the Hawaii Institute of Marine Biology have begun to examine population structure in three species of endemic Hawaiian butterflyfishes: the milletseed butterflyfish (*Chaetodon miliaris)*, the bluestripe butterflyfish *(C. fremblii)* and the pebbled butterflyfish (*C. multicinctus*). Thus far, they have collected and sequenced 170 individuals of bluestripe butterflyfish (Figure 9.25), 229 milletseed butterflyfish (Figure 9.26) and have made significant progress in collections of pebbled butterflyfish (Figure 9.27) throughout the Hawaiian Islands (M.T. Craig et al., pers comm.). These species perform distinct roles in the coral reef ecosystem and can provide examples of differential connectivity over meso-scale distances.

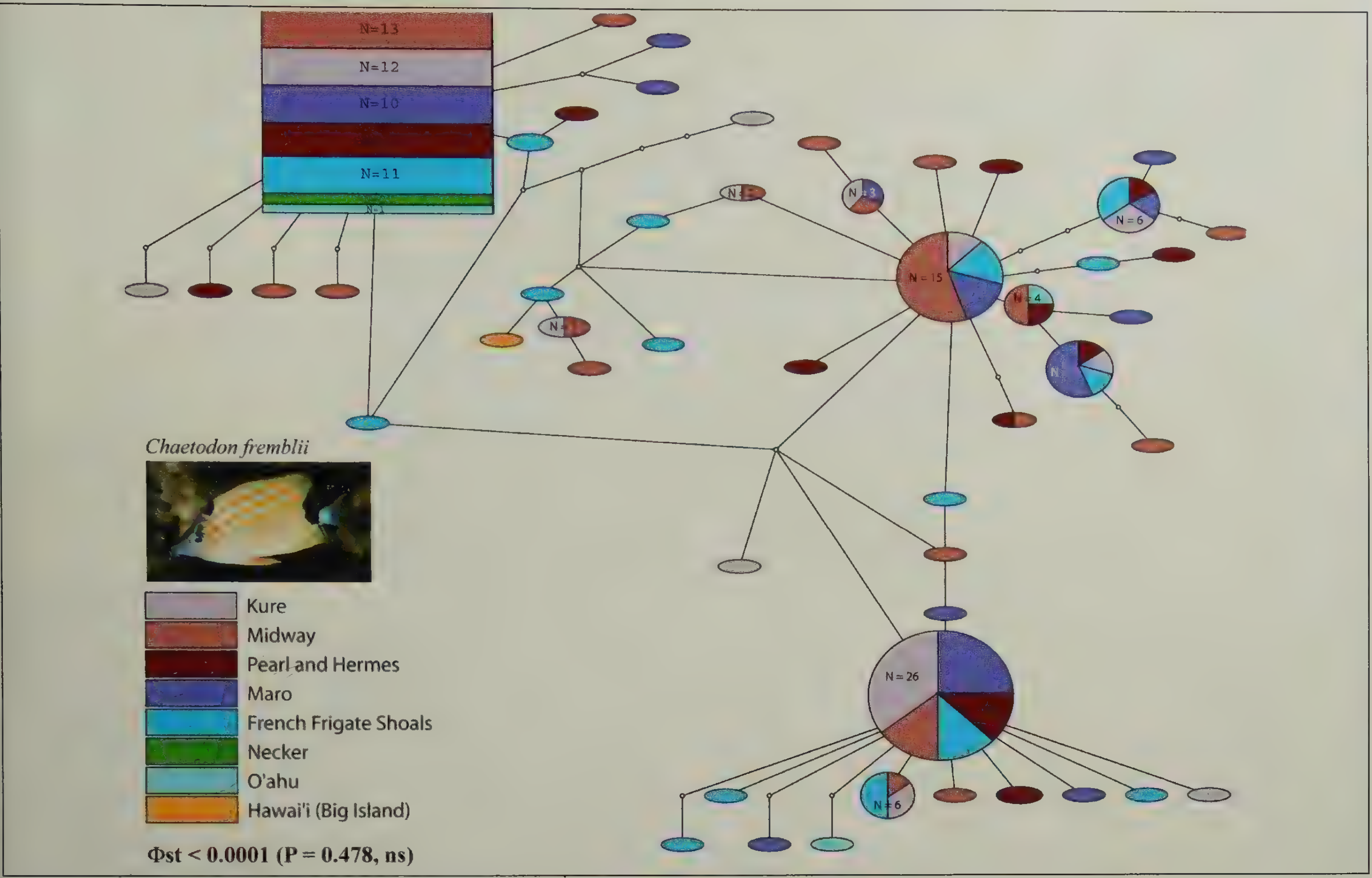


Figure 9.25. Haplotype network for the endemic bluestripe butterflyfish. Source: Craig et al., unpub. data.

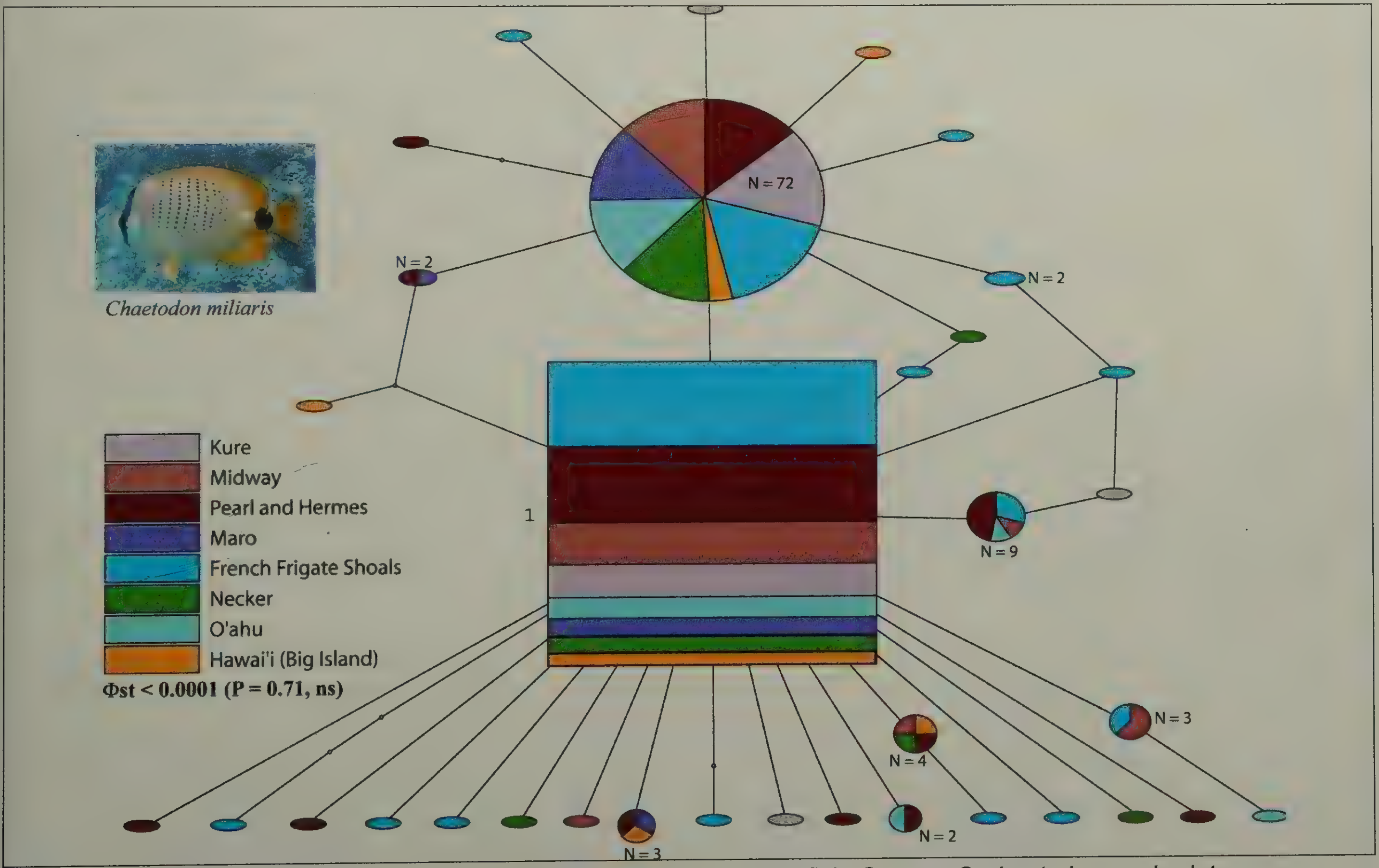


Figure 9.26. Haplotype network for of the endemic milletseed butterflyfish. Source: Craig et al., unpub. data.

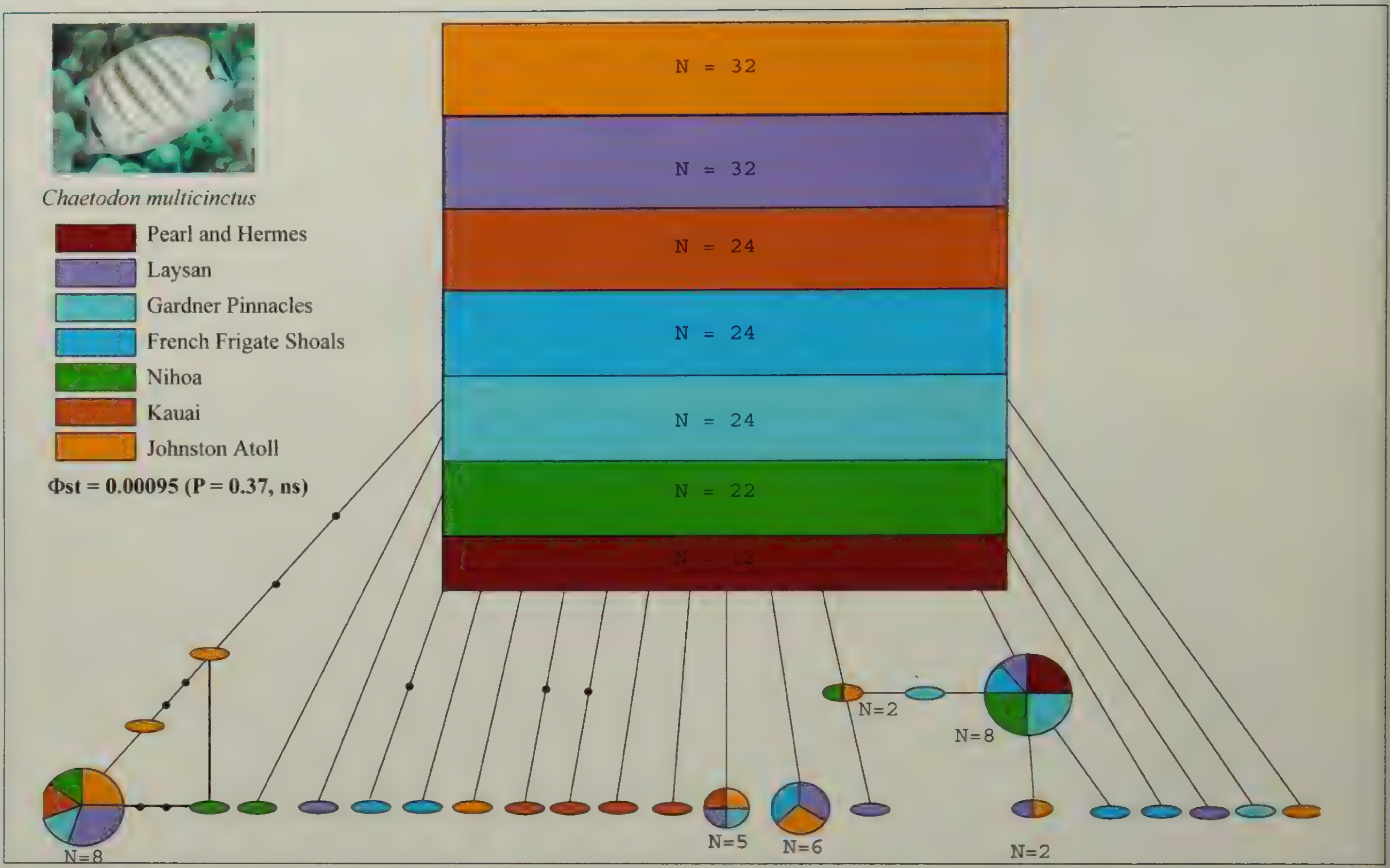


Figure 9.27. Haplotype network for of the endemic pebbled butterflyfish. Source: Craig et al., unpub. data.

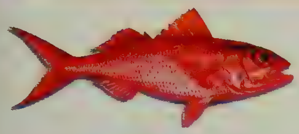
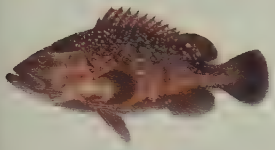
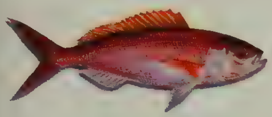
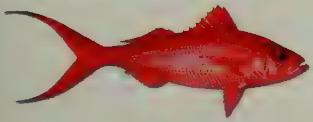
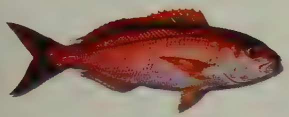
ESSENTIAL FISH HABITAT

Fisheries-habitat links are an important consideration with respect to forms of spatial management such as marine protected areas. The composition of suitable habitat within an area can largely dictate fish distribution and abundance patterns. The formal concept of essential fish habitat (EFH) was defined with the reauthorization of the U.S. Magnuson-Stevens Fishery Conservation and Management Act in 1996, and refers to habitat that is recognized as ecologically important to fisheries resources. Critical fisheries habitats must be identified as valued ecosystem components in order to facilitate the formation of ecosystem-based management actions.

Congress defined EFH as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" (16 U.S.C. 1802(10)). The EFH guidelines under 50 CFR 600.10 further interpret the EFH definition as follows: Waters include aquatic areas and their associated physical, chemical, and biological properties that are used by fish and may include aquatic areas historically used by fish where appropriate; substrate includes sediment, hard bottom, structures underlying the waters, and associated biological communities; necessary means the habitat required to support a sustainable fishery and the managed species' contribution to a healthy ecosystem; and "spawning, breeding, feeding, or growth to maturity" covers a species' full life cycle.

Analysis was conducted for NWHI bottomfish to determine EFH for these important resource species harvested by Hawaiian-based vessels. The bottomfish fishery has targeted about a half-dozen species of deep-slope (generally >75-100 fm) eteline snappers (family Lutjanidae) and one endemic species of epinepheline grouper (family Serranidae) out of a total of a dozen common Bottomfish Management Unit Species (WPFMC 2004; Table 9.1). These species typically inhabitat depth ranges from 100 and 400 m and have been found to be associated with certain benthic features, such as high-relief hard-bottom slopes (Kelley, et al., 2006; Kelley and Ikehara, 2006; Kelley, 2000).

Table 9.1. Dominant species in NWHI bottomfish catch and research-based essential fish habitat boundaries (depth in meters). Illustrations by Les Hata from Hawaii Divison of Aquatic Resources.

	LOCAL NAME	COMMON NAME	SCIENTIFIC NAME	DEPTH RANGE (m)
	Ehu	Red snapper	*Etelis carbunculus*	100-400
	Gindai	Flower snapper	*Pristipomoides zonatus*	100-350
	Hapuupuu	Hawaiian grouper	*Epinephelus quernus*	30-300
	Kalekale	Von Siebold's snapper	*Pristipomoides sieboldii*	50-350
	Lehi	Reddish snapperfish	*Apharues rutilans*	50-250
	Onaga	Scarlet snapper	*Etelis coruscans*	100-400
	Opakapaka	Pink snapper	*Pristipomoides filamentosus*	50-300

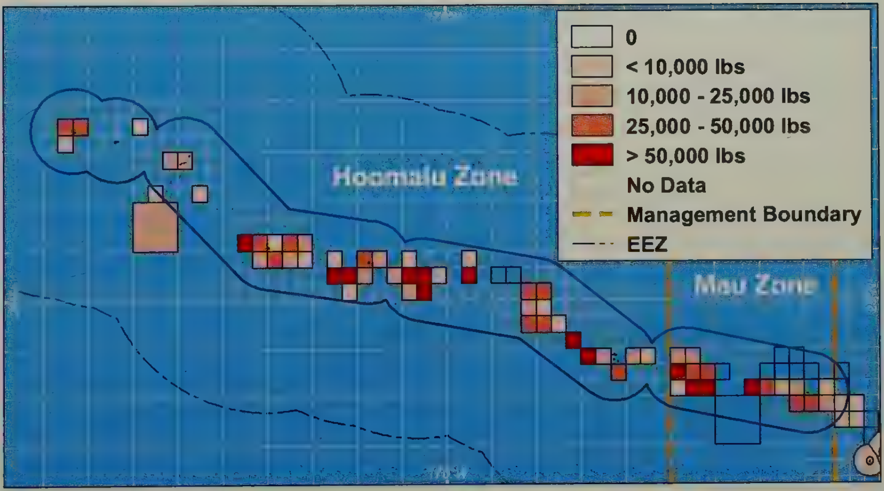


Figure 9.28. Total commercial bottomfish landings from 1996 to 2002. Data in several cells can not be shown due to confidentiality concerns. Data: DAR; Ehler, 2004.

The NWHI fishery is divided into two management zones (Mau, Hoomalu), partly in order to distinguish between short- and long-duration fishing trips and short-duration trips to the closer (to the MHI) Mau and more distant (Hoomalu) zones, respectively (Figure 9.28). Between 1996 and 2004, the Mau zone bottomfish catch (Figure 9.29) was dominated by shallow-water species such as jobfish (39%) and thicklipped jack (butaguchi, *Pseudocaranx dentex*, 14%), with pink snapper (opakapaka, *Pristipomoides filamentosus*, 13%), Hawaiian grouper (hapuupuu, *Epinephelus quernus*, 13%), and red snapper (onaga, *Etelis coruscans*, 8%). In contrast, red snapper and pink snapper accounted for 28% and 25% of the Hoomalu catch, respectively, followed by Hawaiian grouper (15%).

The average annual reported landings of bottomfish in the NWHI between 1984 and 2003 were 336,000 lbs (SD ± 235,500; NOAA 2006). Of this, the Mau zone averaged 107,130 (SD ± 53,890) or 32% while the average catch in the Hoomalu zone averaged 228,730 lbs (SD ± 63,030) or 68% (Figure 9.29). In 2003, the gross reported revenues for the Mau zone were $611,000 and $674,000 for the Mau and Hoomalu zones, respectively (Ehler, 2004).

In 2003, the number of vessels participating in the two zones remained the same from the previous year, but there were substantial changes in the number of fishing trips (NOAA, 2006). In 2003, Mau zone trips decreased by 51% resulting in a 29% drop in landings from the previous year. The number of trips in the Hoomalu zone increased by 50% in 2003, resulting in a 29% increase in landings.

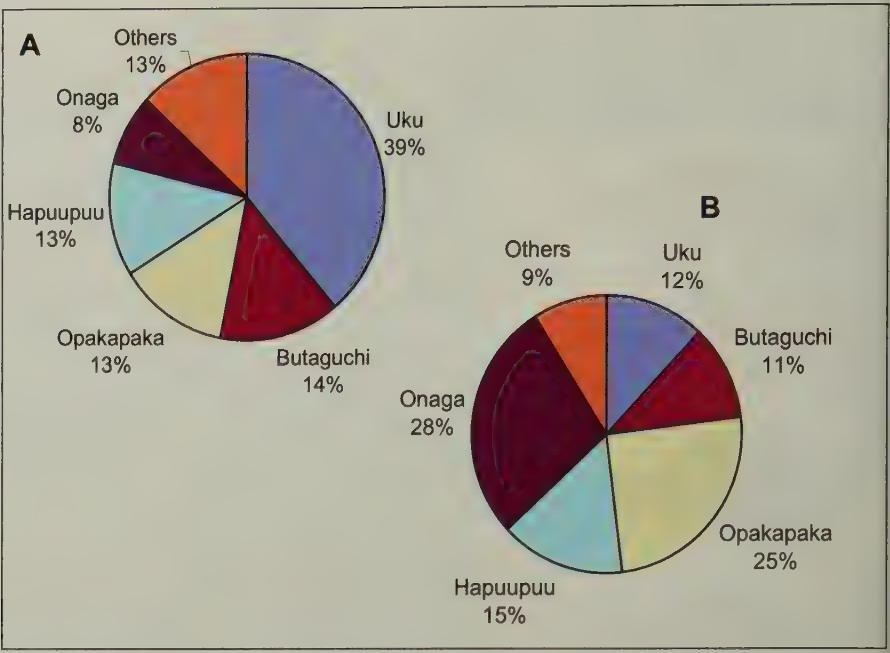


Figure 9.29. Average species composition (1996-2004) of bottomfish catches from the Mau (A) and Hoomalu (B) zones in the NWHI. See text for scientific and common names. Source: Kawamoto and Gonzales, 2005.

With the initial designation of the NWHI Coral Reef Ecosystem Reserve and now PMNM, fishing activity in the NWHI has been on the decline. Proclamation 8031 allows commercial fishing by federally permitted bottomfish fishery participants that have valid permits until mid-2011 (FR 36443, June 26, 2006). This amounts to a maximum of eight permitted bottomfish vessels that fish within the Monument. Significant work was undertaken prior to the designation of the Monument in response to previously issued Executive Orders that created the Reserve in 2000. This fishery operates according to the management regime specified in the Fishery Management Plan for Bottomfish and Seamount Groundfish Fisheries in the Western Pacific Region. The management regime includes several precautionary measures that minimize potential effects of this fishery. The bottomfishery participants do not operate in the presence of the Hawaiian monk seals and the annual harvest limit for the eight vessels is 300,000 lbs.

Table 9.2. Optimal bottomfish habitat criteria for NWHI. Source: PIBHMC.

GIS LAYER	SOURCE	RANGE
Depth	PIBHMC 20 m multibeam data	100-400 m
Slope	Derived from PIBHMC 20 m multibeam data	> 20 percent slope
Backscatter	R/V *AHI*	Hard (>120 m)
Backscatter	R/V *Kilo Moana*	Hard (> 1,000 m)

The criteria used to delineate potential bottomfish habitat in the NWHI was based on previous analysis done in the MHI (Kelley, 2000; Parke, 2007). Multibeam data sonar provided the GIS layers for bottom depth, slope and hardness. These factors were used as criteria to identify EFH and potential adult habitat for bottomfish (Table 9.2). The depth range found most appropriate for this analysis was 100-400 m based on EFH criteria. Areas with slopes greater than 20% were then selected in the GIS to further delimit the potential adult habitat areas. Lastly, areas designated as hard bottom based on backscatter values were selected for the final potential adult habitat delineation. The range of sonar backscatter values depended upon the instrument used to collect the data.

Table 9.3. Area (km^2) of EFH based on available multibeam data detailing depth (100-400 m) within each island. Source: PIBHMC.

ISLAND AREA	EFH (km^2)	% OF TOTAL MAPPED AREA
French Frigate Shoals	243.93	23.51
Kure	138.79	31.19
Maro	407.97	30.32
Pearl and Hermes Atoll	54.12	10.98
Total km^2	**844.81**	**24.00**

EFH and potential adult habitat analysis was completed for French Frigate Shoals, Kure, Maro, and Pearl and Hermes because these islands had sufficient multibeam data. These islands currently do not have complete coverage in the depth range designated for EFH, so the results of this analysis represent bottomfish EFH and potential adult habitat based on the data available to date. Maps for each island were created for areas that met each of the criteria. The areas in these map products that met all three criteria were considered to be "suitable" adult bottomfish habitat (Table 9.3; Figure 9.30).

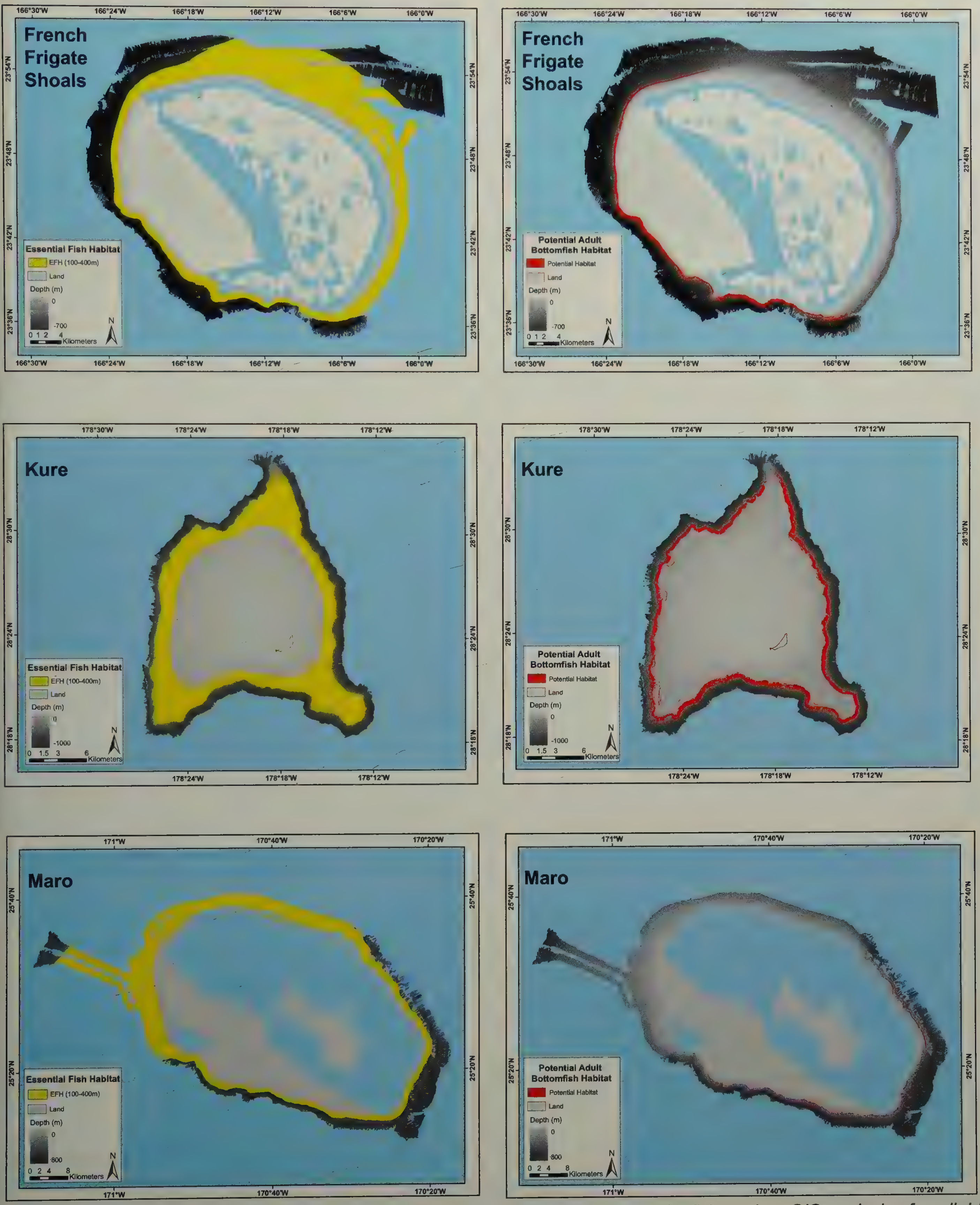


Figure 9.30. Essential fish habitat (yellow) and potential adult bottomfish habitat (red) based on GIS analysis of available multibeam data. Maps: L. Wedding.

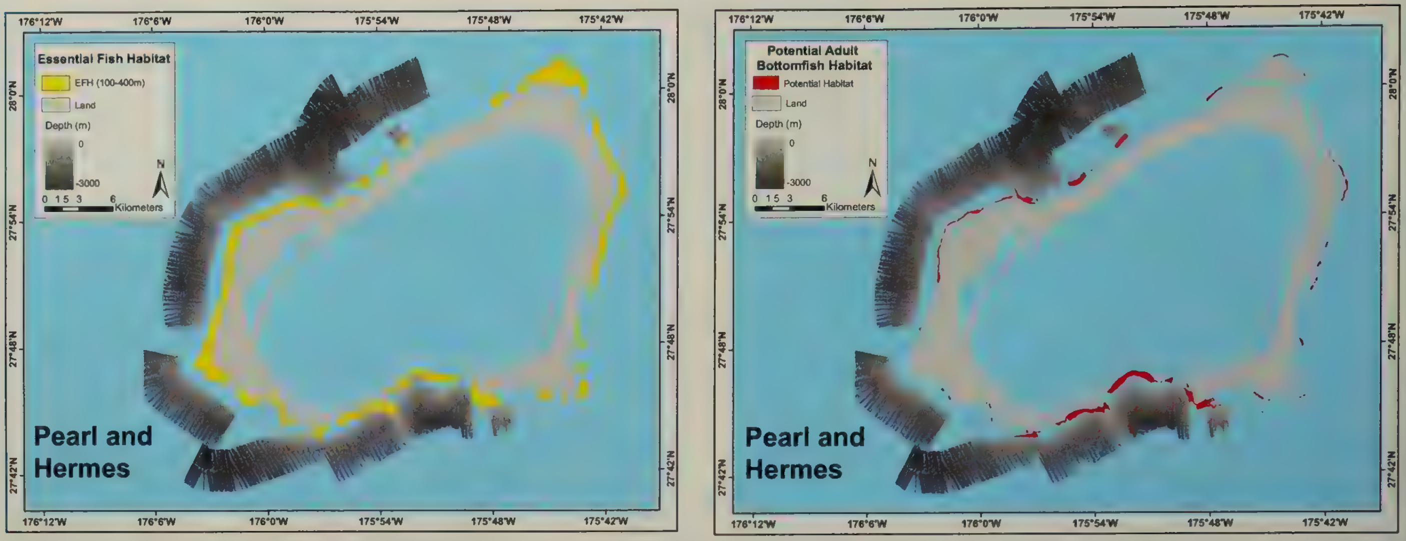


Figure 9.30 (continued). Essential fish habitat (yellow) and potential adult bottomfish habitat (red) based on GIS analysis of available multibeam data. Maps: L. Wedding

TROPHIC RELATIONSHIPS: STABLE ISOTOPE COMPOSITION OF PRIMARY PRODUCERS AND CONSUMER ORGANISMS

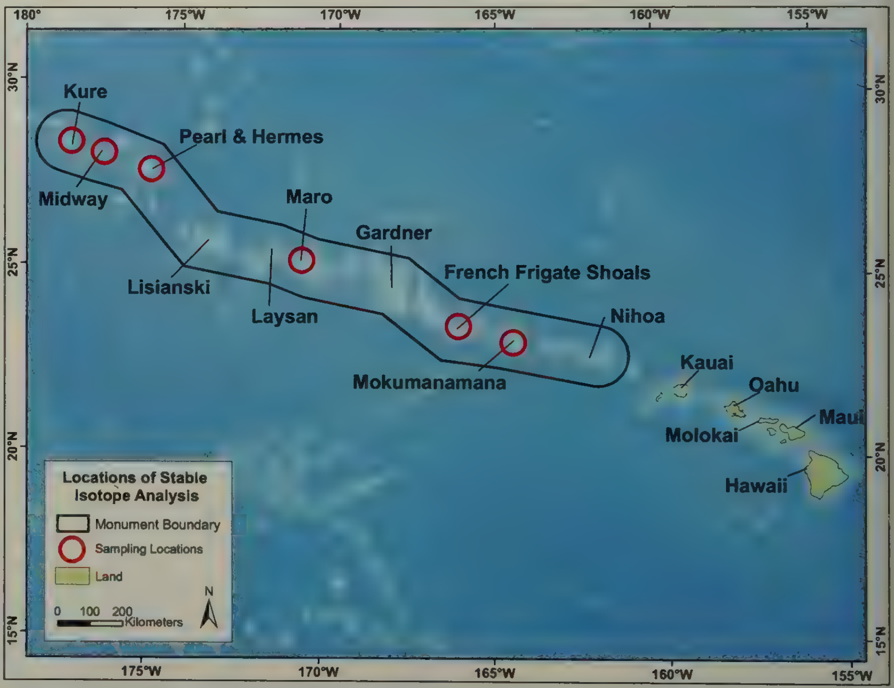


Figure 9.31. Locations for stable isotope analysis from cruises in April, May and September 2005. Map: L. Wedding.

Analysis of the carbon (C) and nitrogen (N) stable isotope composition of primary producers, benthic invertebrates, bony (teleost) fishes and sharks was used to assess vertical trophic linkages between primary producers and consumer organisms in the NWHI, and horizontal trophic linkages between reef and pelagic ecosystems. Samples of fish, sharks, invertebrates, phytoplankton and benthic algae were obtained during a May 2005 cruise aboard the NOAA ship *Hiialakai* from six locations in the NWHI (Figure 9.31). Muscle tissue was removed from fish (dissection), sharks (plugs from tagged animals), and invertebrates (dissection). Animal tissue was rinsed in distilled water, dried and ground prior to stable isotope analysis. Seawater was prefiltered through a 200 micron mesh to remove zooplankton and retain phytoplankton on ashed glass fiber filters. Benthic macroalgae were collected by divers, cleaned and rinsed in distilled water, dried and ground. Benthic microalgae were collected by divers from surface sediments. Microalgae were separated from sediment either by vertical migration through nylon mesh (Currin et al., 2003) or by density centrifugation in colloidal silica (Moseman et al., 2004). Algal samples were fumed with concentrated hydrochloric acid to remove carbonates prior to stable isotope analysis. All samples were sent for analysis of ^{13}C and ^{15}N composition by mass spectrometry at the University of California-Davis.

The C and N stable isotope composition of algae is a function of ocean chemistry, photosynthesis and growth rates, and the specific nitrogen uptake mechanisms of the algae. Typically, phytoplankton have a C isotopic signature distinct from benthic algae, and this distinction can be followed through a food web, as animals are usually within 0.5‰ of the ^{13}C value of their food. In contrast, algae differ less in their□ ^{15}N values, and animals usually have ^{15}N values that are 2.5 to 4 ‰ greater than their food, and so N isotopes provide a means to calculate the number of trophic steps between primary production and a higher level consumer.

Fish collected from the NWHI were assigned to one of seven trophic groups using diet information in Friedlander and DeMartini (2002) and Parrish and Borland (2004). Invertebrates, which consisted of Hawaiian spiny lobster and a single Hawaiian day octopus, were placed in a separate group. All sharks were classified as apex predators; see Table 9.4 for list of species collected, trophic group assignments and number of samples collected.

Table 9.4. Trophic group assignments for species collected for stable isotope analysis. Number of samples analyzed (n) and common names are also provided.

TROPHIC GROUP	GENUS SPECIES	COMMON NAME	n
Herbivores	*Acanthurus olivaceus*	orangeband surgeonfish	30
	Acanthurus nigrofuscus	brown surgeonfish	4
	Acanthurus triostegus	convict tang	35
	Acanthurus nigroris	bluelined surgeonfish	23
	Stegastes fasciolatus	Pacific gregory	5
	Zebrasoma flavescens	yellow tang	22
Corallivore	*Chaetodon lunulatus*	oval butterflyfish	15
Zooplanktivores	*Chaetedon milaris*	milletseed butterflyfish	54
	Dascyllus albisella	Hawaiian dascyllus	18
	Myripristis berndti	big-scale soldierfish	3
	Myripristis amaena	brick soldierfish	3
	Priacanthus meeki	Hawaiian bigeye	16
Invertebrates	*Octopus cyanea*	Hawaiian day octopus	1
	Panulirus marginatus	spiny lobster	42
Benthic predators	*Lutjanus kasmira*	bluestripe snapper	11
	Parupeneus porphyreus	whitesaddled goatfish	14
	Parupeneus multifasciatus	manybar goatfish	37
	Pareupeneus cyclostomus	yellowsaddle goatfish	2
	Bodiandus bilunulatus	Hawaiian hogfish/wrasse	15
	Chaetodon fremblii	bluestripe butterflyfish	30
	Thalassoma ballieui	blacktail wrasse	29
Pelagic predators	*Euthynnus affins*	wavy-backed tuna	5
Apex predators	*Caranx melampygus*	blue jack	19
	Caranx ignobilis	white jack	36
	Aprion virescens	green jobfish	6
	Carcharhinus amblyrhynchos	grey reef shark	6
	Carcharhinus galapagensis	Galapagos shark	28
	Galeocerdo cuvier	tiger shark	8
	Epinephelus quernus	Hawaiian grouper	2

There was a clear separation in the ^{13}C signatures of the primary producers in the NWHI system. Phytoplankton (Phyto) had an average ^{13}C value of -23.4‰, consistent with other published values for oceanic phytoplankton. Benthic macroalgae (BMA) and microalgae (BMI) were relatively enriched in ^{13}C, with average values of -18.2 and -9.5 ‰, respectively. There was less separation in the mean ^{13}N values of benthic algae, which ranged from 1.1 to 3.4 ‰ (Figure 9.32).

Fish which were a priori placed in the Herbivore category had lower ^{15}N values than other consumer organisms, as expected. However, the offset between the ^{15}N values of algae and several members of the Herbivore group was higher than the expected 2 to 4/mil, suggesting that either some of the fish designated as herbivores are in fact omnivores, or that the algal N values obtained during the May 2005 cruise were more depleted than algal values earlier in the season. This latter point can reasonably explain the observed data, as the isotope composition of fish tissue turns over much more slowly than the isotopic composition of the faster growing algae. There was also a significant range in the C values within the Herbivore group, with yellow tang in particular closest to the phytoplankton endmember, and the brown surgeonfish closest to the benthic microalgal endmember. Both yellow tang and brown surgeonfish are browsers of macroalgae but isotopic differences suggest there may be finer scale variations in diet (Jones, 1968).

Fish designated as Zooplanktivores and Corallivores, as well as lobster and octopus, had ^{15}N values of approximately 8.25‰, consistent with feeding at two trophic levels above primary producers with an average ^{15}N trophic fractionation value of 2‰. The Zooplanktivores had the lowest C isotope signature, suggesting a greater contribution of phytoplankton to their food web, although a significant portion of benthic production was also utilized by this group. In contrast, the Corallivore had a more enriched C isotope signature, consistent with a greater contribution of coral and benthic algae to its food web.

Fish designated as Benthic Predators exhibited approximately a 3‰ range in both C and N isotope signatures. Benthic Predators with ^{15}N values >10 (blacktail wrasse) may be feeding 2.5 to 3.0 trophic levels above the primary producers. The Benthic Predators with the most enriched ^{13}C values were the whitesaddle goatfish and the Hawaiian hogfish,

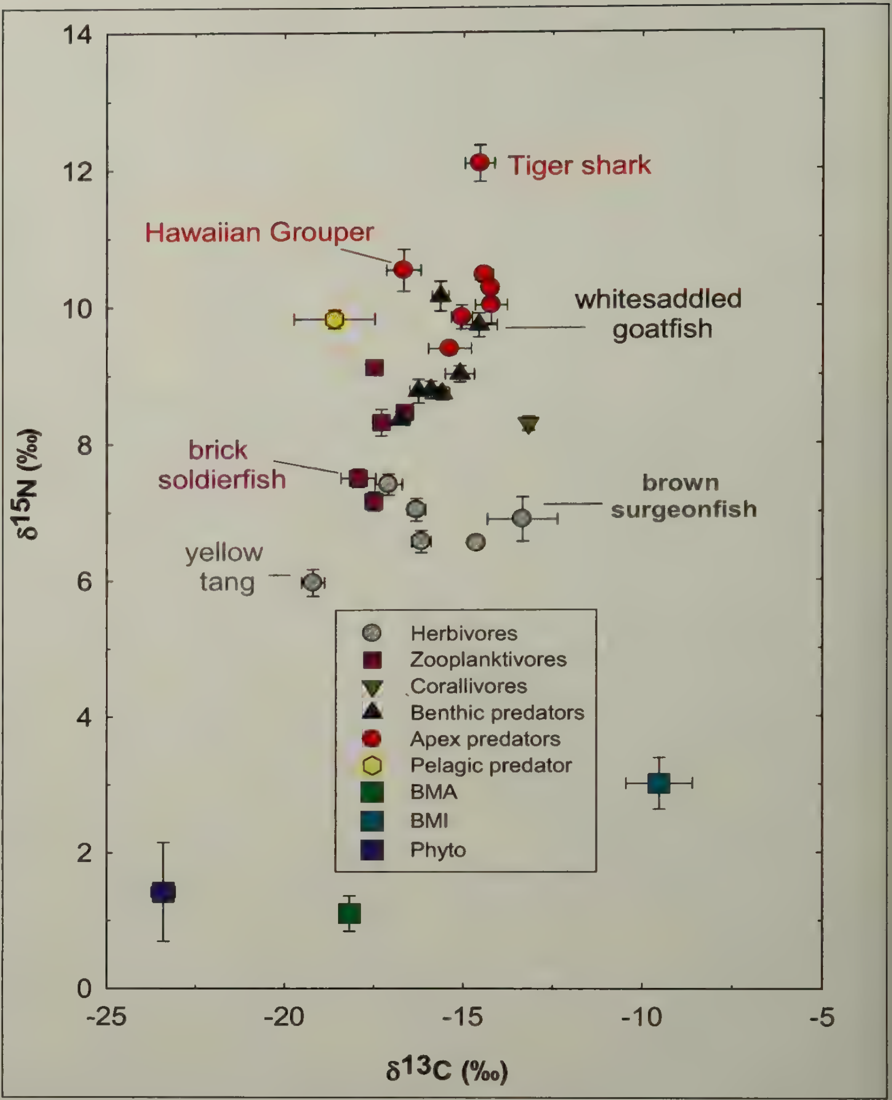


Figure 9.32. Dual isotope plot of consumer and producer groups from NWHI. Each symbol represents the mean ± one standard error of the ^{15}N or ^{13}C value for a species of fish, shark or invertebrate. Species list, number of samples and trophic group designations are as in Table 9.4; arrows point to species referred to in the text.

The ^{13}C values of fish designated as Pelagic Predators were relatively depleted in ^{13}C, suggesting that phytoplankton did contribute substantially to the food webs supporting these fish. The ^{15}N values of Pelagic Predators averaged 9.3‰, which is very similar to the average trophic level of the Benthic Predator group, and consistent with an organism feeding two to three levels above the primary producers.

The ^{15}N values of fish and sharks designated as Apex Predators overlapped with the ^{15}N values of the Pelagic Predator (wavy-backed tuna) or Benthic Predator (blacktail wrasse). The exception is the enriched ^{15}N value of 12.1 for the tiger shark, which puts it nearly a full trophic level above other predators in the NWHI ecosystem. This is consistent with marine mammals, sharks, birds and other upper trophic level prey comprising a larger portion of the tiger shark diet than that of Galapagos and grey reef sharks (Papastamatiou et al., 2006). The ^{13}C values of several of the Apex Predator group were enriched in ^{13}C compared to other predators in the system. In particular, it appears that grey reef sharks, Galapagos sharks, giant trevally, and tiger sharks are obtaining the bulk of their C from a benthic-based food web.

The relative contribution of benthic primary production to the food webs supporting bony fish, shark and invertebrate production can be estimated by comparing the stable isotopic composition of these groups with values that would be expected from a prescribed food web. In Figure 9.33, the mean isotope values of each of the trophic groups described in Table 9.4 are displayed. The black dotted lines in the figure represent the expected graphical position of a consumer group feeding at the first Trophic Level (1 TL) through the fourth Trophic Level (4 TL). The position of these black lines is based on the assumption that there is a 2 – 4‰ increase in ^{15}N values per trophic step, and a 0.5‰ increase in ^{13}C values per trophic step, and that the food web is based on equal parts phytoplankton, benthic microalgae, and benthic macroalgae. In terms of trophic level of the various groups, the figure clearly illustrates the discrepancy between the 15N values of the primary producers as measured in May 2005 and the herbivores that are presumably grazing on them. As noted previously, this could be due to a short-term decrease in the ^{15}N values of the primary producers, and the longer-term average value of the primary producers may be closer to 3.5 – 4.5‰, which would result in the observed herbivore ^{15}N values. Alternatively, it may be that some members of the group designated as 'Herbivores' are in fact. Figure 9.33 also clearly illustrates that the groups designated as Zooplanktivores, Corallivores and Invertebrates (lobster) are feeding a full trophic level above the Herbivores, and that the Benthic and Pelagic Predator groups are feeding about one-half trophic level above that position. Apex Predators (sharks and jacks) are feeding nearly a full trophic level above the Invertebrate/Corallivore level, and about one-half trophic level above the Benthic and Pelagic Predators. As noted previously, and illustrated in Figure 9.32, tiger sharks are an exception and are feeding a full trophic level above the Benthic Predator group. The figure also reveals that all groups other than Pelagic Predators, Zooplanktivores and Corallivores fall roughly where they would be expected to fall if phytoplankton represented approximately 33% of the base of their food web, with the remaining portion deriving from equal parts benthic microalgae and benthic macroalgae. The position of the exceptions indicate that phytoplankton represent a greater proportion of the food web support for Pelagic Predators and Zooplanktivores, and that phytoplankton represent less than a third of the food web support for Corallivores. Taken together, these results from analysis of the stable isotope composition of primary producers and consumers from the NWHI are remarkably consistent with the Ecopath model estimates of the food web supporting fishery production in the NWHI (see next section). Both approaches indicate that benthic algae provide the majority of trophic support for apex predators, and that the entire system consists of a relatively short (three to four trophic levels above primary production) food chain.

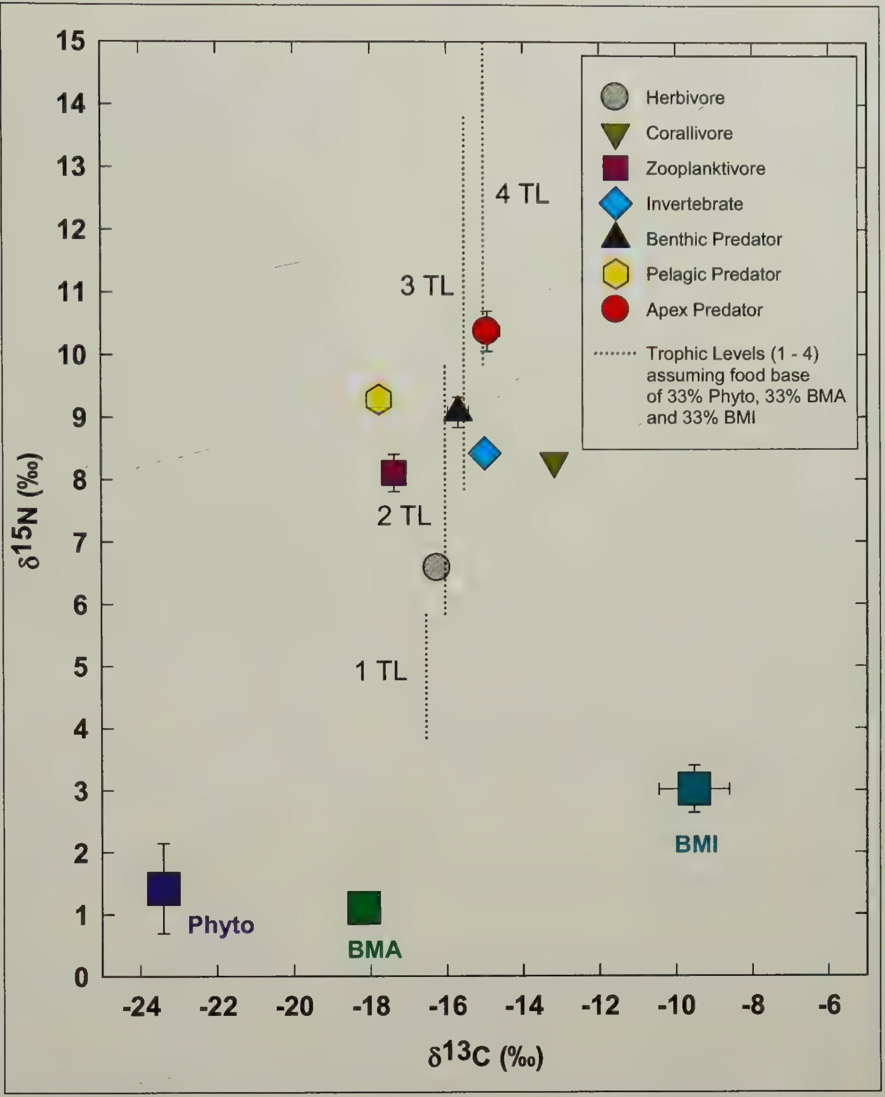


Figure 9.33. Dual isotope plot of mean isotope values of primary producers and each of the trophic groups described in Table 9.4. The black dotted lines in the figure represent the expected graphical positions of a consumer group feeding at the first Trophic Level (1 TL) through the fourth Trophic Level (4 TL), assuming a food web based on equal parts of each of the three primary producers (phytoplankton, benthic macroalgae, benthic microalgae). Further details on assumptions are in the text.

FOOD WEB MODELS

The coral reefs of the NWHI represent a diverse marine ecosystem that provides habitat to a number of organisms (Figure 9.34). In the mid to late 1970s, dozens of scientists participated in a large, multi-year field study program at French Frigate Shoals to describe and better understand this ecosystem (Grigg et al., 2008). These efforts yielded Ecopath, a simulation program designed to model the flow of energy throughout the system. Ecopath works by creating a snapshot of the ecosystem and the feeding relationships between species within that ecosystem. The trophically linked components consist of a single species, or a group of species representing ecological levels. For each species group, biomass, production/biomass ratio (or total mortality), consumption/biomass ratio and ecotrophic efficiency are measured (Polovina, 1984). Ecosim, a new dynamic modeling program based on the original Ecopath model, is now available at (http://www.ecopath.org).

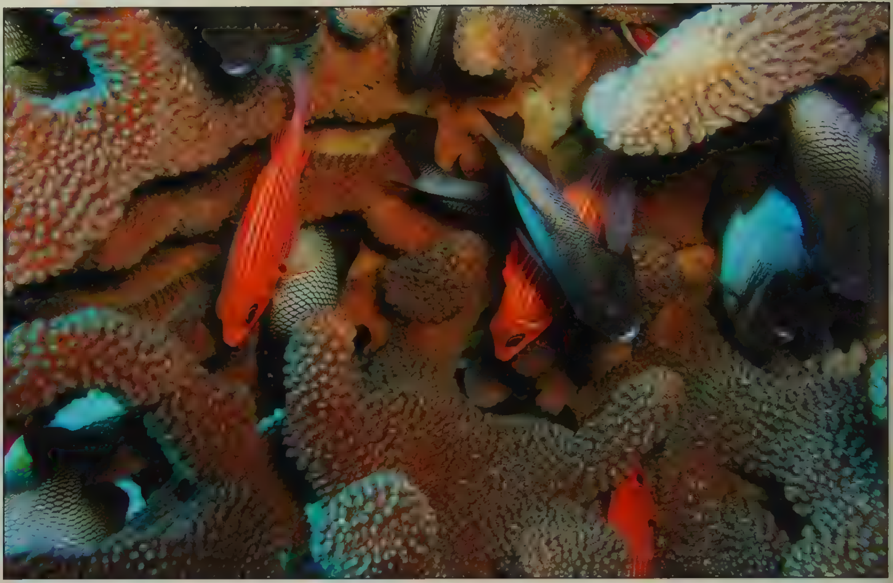


Figure 9.34. The coral reefs of the NWHI are a very diverse and unique ecosystem, providing habitat for a wide range of marine life. Photo: J. Maragos.

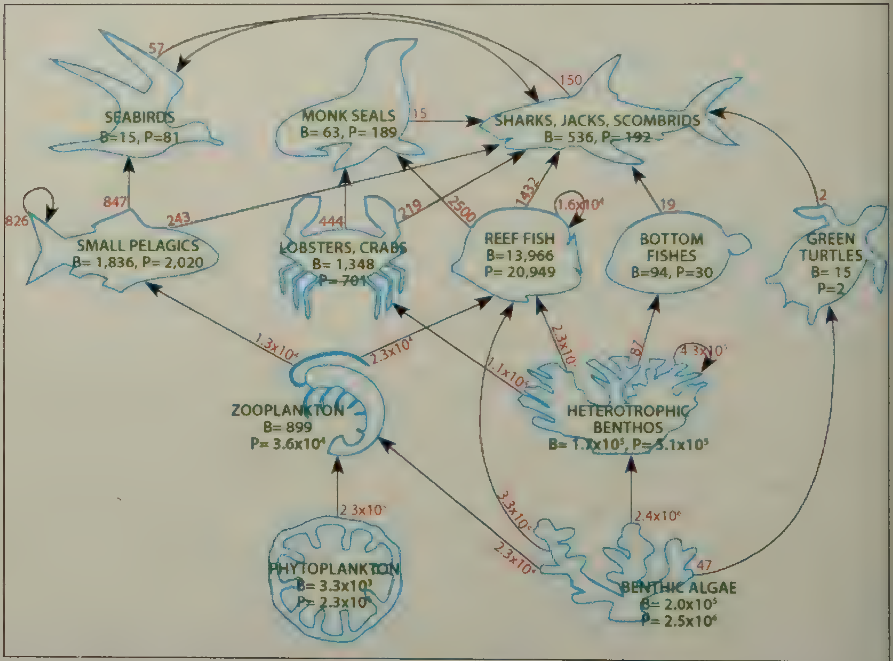


Figure 9.35. Illustration of the Ecopath Model for the food web at French Frigate Shoals. The trophic pathway, annual production (P), and mean annual biomass (B; kg/km^2) is given for 12 species groups based on an area of 1,200 km^2. Source: Polovina, 1984.

Ecopath was first applied to data collected at French Frigate Shoals during the late 1970s (Figure 9.35). The ecosystem was divided into 12 species groups with sharks, jacks, monk seals, sea birds and tuna at the top trophic level, reef fishes at the center, and benthic algae, responsible for 90% of the productivity, at the bottom (Polovina, 1984). The large reef fishes group was further divided into four feeding guilds, resulting in an ecosystem spanning almost five trophic levels with sharks, jacks and piscivorous reef fish representing the top predators (Polovina, 1984). With the exception of limited handline fishing for snappers, the NWHI are not fished and experience relatively few, severe local anthropogenic threats (although sea level rise, acidification, and the warming/bleaching and loss of coral habitat will likely become a major human agent of change at basin and global scales later in this century). Because the NWHI presently has few severe local threats, the Ecopath model provides a picture of an increasingly rare coral reef ecosystem dominated by an abundance of apex predators.

The Ecosim was used to simulate changes in ecosystem dynamics over time in response to top-down or bottom-up forcing (Christensen and Walters, 2004) which was modelled by assuming 30 years of high benthic primary productivity, followed by 30 years of low benthic primary productivity (Grigg et al., 2008). Significant temporal lags, varying by as much as a decade, were observed in the responses of the various trophic guilds both under an increase and a decrease in benthic productivity (Grigg et al., 2008). Planktivorous reef fish trended downward when benthic productivity was high due to the increase in predatory species (e.g., jacks). This was the case even when prey plankton was unchanged. When benthic productivity was changed from high to low there was an immediate sharp increase followed by a decline in benthic carnivorous reef fishes. The reef fishes quickly increased in abundance in response to higher prey availability, but five years later as their predators increased, their abundance declined (Grigg et al., 2008). Even with the more complex Ecosim model, it is important to note that ecosystem dynamics are more complicated than the model provides and are not always consistent with model forcing.

In the last 10 years the Ecosim model was revised using updated parameters and a reference biomass based on surveys of benthic/demersal fish taxa that exhibited habitat fidelity (Parrish, unpub data). Field surveys were spatially stratified by the region's primary habitat types in order to make the model more accurate (Grigg et al., 2008). The surveyed fish communities occupied the central portion of the ecosystem food web and were used to project a minimum biomass for the lower guilds, as well as a theoretical maximum value for the top level transient predators that preyed on the fish (Grigg et al., 2008). Work is now underway to validate the model with the best field estimates of population size, body size distributions, and size-specific food and feeding habits for the endangered Hawaiian monk seal, a top level predator in the NWHI. Numbers and body condition of the seals have been closely monitored for the last two decades and foraging studies indicate a diet of primarily benthic/demersal fish (Goodman-Lowe, 1998; Parrish et al., 2000, 2002 and 2005). Successful validation of the model using monk seals will depend on knowing the boundaries of the seal foraging activity and the relative composition of the diet (Grigg et al., 2008). Once initial validation efforts are complete, the dynamic simulation phase using Ecosim (Figure 9.36) will begin with the goal of forecasting and hindcasting situations to illustrate how the system might react to both natural and anthropogenic stressors.

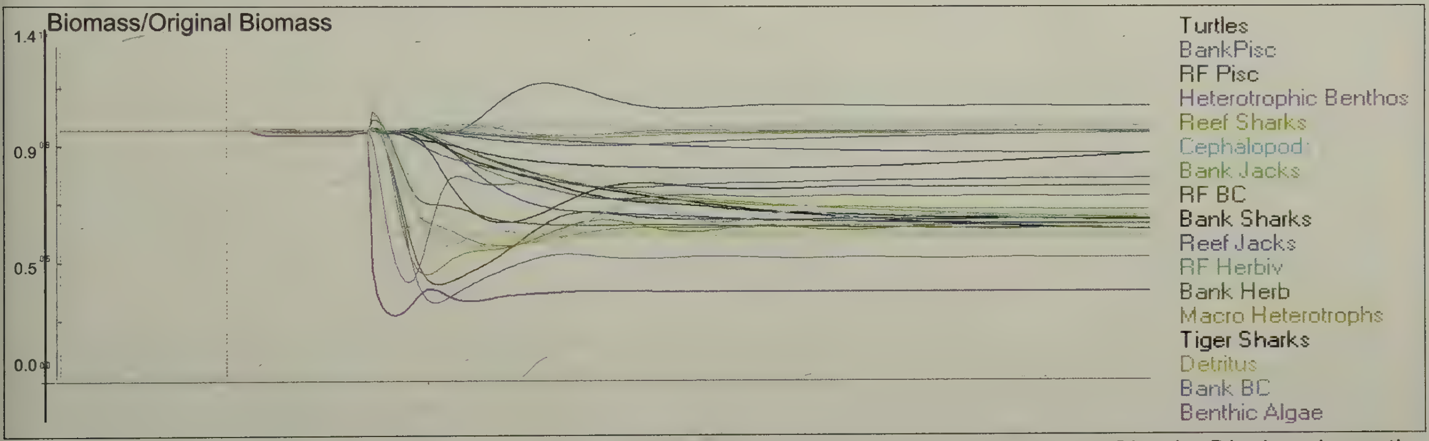


Figure 9.36. Capture of the Ecosim software output for the Ecopath model at French Frigate Shoals. Display shows the response of ecosystem component to a 50% reduction in benthic algae.

EXISTING DATA GAPS

To understand passive transport, there is a need for basic information on spatial and temporal patterns of water movement, quality and characteristics within the NWHI at a range of scales to determine the general patterns of passive transport for nutrients and living resources. Building on an understanding of oceanographic processes, specific research needs and opportunities include efforts to:

- Determine the transport pathways and patterns for the larvae of key organisms;
- Identify the sources and sinks of larval dispersal for key organisms;
- Define the sources and patterns of primary productivity resulting from upwelling sites and occurrences and nutrient input to the NWHI; and
- Undertake applied research into the design of protected areas in support of ecosystem resilience based on passive transports processes, patterns and pathways.

Overall there is a need for systematic information on the active transport and movement of biota into, out of and within the NWHI. This work can be extended to important applications such as stock identification, population dynamics and species interactions. All of these efforts should be undertaken in a way that contributes to the development of models that can predict movement patterns at multiple spatial scales to address questions of connectivity, including the linkages between the NWHI and the MHI.

Specific opportunities include research to improve the understanding of:

- What are the important species that have regular or episodic, active movements or migrations into and out of the NWHI and MHI?
- What life stages of these species are involved in the active movements?
- What are the important habitats for different life stages of these species that move among the reefs within the NWHI and between the NWHI and MHI?
- What are the effects of extreme events and anthropogenic stressors on movements and migrations?
- Which habitats are at risk from climate change and other forces (e.g., sea turtles and their nesting beach habitat)?

As the understanding of most of the species and populations in the NWHI is at the most basic level (e.g., identification of species and groups), genetic studies have the capability to enhance the understanding of the ecosystem, including distribution, dispersion rates, and connectivity or isolation among plant and animal populations in the NWHI. Specific research opportunities include:

- Characterizing the genetic structure of key species and populations;
- Determining genetically distinct subpopulations of flora or fauna between the MHI and the NWHI;
- Determining the value of selected species in the NWHI for repopulating MHI populations that are over exploited or subject to major impacts;
- Applying genetic techniques to key populations across the stress gradient of the archipelago to detect pools of individuals with a genetic makeup that keeps them from being filtered out by the environmental stressors;
- Studying individual species' response to natural and anthropogenic stress (determining the coral species that are more heat tolerant and can withstand coral bleaching);
- Identifying key species that may be at risk from the genetic influence of invasive species. Identifying pilot taxa to serve as proxies for ecosystem genetic connectivity; and

- Because management decision making will be improved by knowledge of many specific factors influencing ecosystem resilience, information is needed on resilience pathways, such as: acclimation to stress, adaptation to stress, the role of the environment and the role of the community. Specific examples of research opportunities include activities to determine:
    - The key aspects that affect ecosystem stability and resilience (e.g., rates of energy flow, oceanographic conditions, nutrient levels and recruitment);
    - The degree to which natural variability in an ecosystem may determine its capacity for resilience;
    - How ecosystem acclimation to change varies among taxa and in relation to survival and the ability to effectively reproduce;
    - How genetic makeup enhances the ability of taxa to recover from some kinds of stress;
    - Which environmental conditions, e.g., temperature, flow, geomorphology, have a mitigating influence on survival in a changed environment;
    - The extent to which the reduction or expansion of one or more species or functional groups results in top down predation or an increase in bottom up production;
    - How the rebound of an ecosystem depends on maintaining established pathways of energy flow which provide the system a stable means of recovery rather than risk a transition to a different state of equilibrium;
    - The extent to which reducing fish populations of the ecosystem undermine or realign energy flow and trophic stability; and
    - Whether self seeding systems are resilient.

REFERENCES

Andrews, K.R., L. Karczmarski, W.W.L. Au, S.H. Rickards, C.A. Vanderlip, and R.J. Toonen. 2006. Patterns of genetic diversity of the Hawaiian spinner dolphin (*Stenella longirostris*). Atoll Research Bulletin 543: 65-73.

Baums I.B., S. Goodwin, D. Carlon, and R.J. Toonen. In prep. No population differentiation in four coral-reef inhabiting hermit crab species (*Calcinus spp.*) across the Eastern Pacific. Molecular Ecology.

Bernardi, G., S.J. Holbrook, R.J. Schmitt, N.L. Crane, and E. DeMartini. 2002. Species boundaries, populations, and colour morphs in the coral reef three-spot damselfish (*Dascyllus trimaculatus*) species-complex. Proc.Roy. Soc. London 269: 599-605.

Bird, C.E., B.S. Holland, B.W. Bowen and R.J. Toonen. 2007. Contrasting population structure in three endemic Hawaiian limpets (*Cellana* spp.) with similar life histories. Molecular Ecology. 16: 3173-3187.

Christensen, V. and C. J. Walters. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecol. Model. 172: 109–139.

Cowen, R.K., G. Gawarkiewicz, J. Pineda, S.R. Thorrold, and F.E. Werner. 2007. Population connectivity in marine systems: an overview. Oceanography 20(3): 14-21.

Cowen, R.K., C.B. Paris, and A. Srinivasan. 2006. Scaling Connectivity in Marine Populations. Science 311: 522-527.

Craig, M.T., J.A. Eble, D.R. Robertson, and B.W. Bowen. 2007. High genetic connectivity across the Indian and Pacific Oceans in the reef fish Myripristis berndti (Holocentridae). Marine Ecology Progress Series 334: 245-254.

Crowder, L.B., S.J. Lyman, W.F. Figueira, and J. Priddy. 2000. Sourcesink population dynamics and the problem of siting marine reserves. Bull Mar Sci 66: 799–820.

Currin, C. A., S.C. Wainright, K.W. Able, and M. P. Weinstein. 2003. Determination of food web support and trophic position of the mummichog, Fundulus heteroclitus, in New Jersey smooth cordgrass (*Spartina alterniflora*), common reed (*Phragmites australis*) and restored salt marshes. Estuaries 26: 495-510.

DeMartini, E.E. and A.M. Friedlander. 2004. Spatial pattern of endemism in shallow water reef fish populations of the Northwestern Hawaiian Island. Mar. Ecol. Prog. Ser. 271: 281-296.

Ehler, R. 2004. Socio-economic assessment of commercial bottomfishing in the Northwestern Hawaiian Islands. Report to NOAA,NOS, National Marine Sanctuary Program. 46 pp.

Friedlander, A.M. and E.E. DeMartini. 2002 Contrasts in density, size and biomass of reef fishes between the Northwestern and Main Hawaiian Islands: the effects of fishing down apex predators. Mar. Ecol. Prog. Ser. 230:253-264.

Goodman-Lowe, G. D. 1998. Diet of the Hawaiian monk seal (*Monachus schauinslandi*) from the Northwestern Hawaiian Islands during 1991-1994. Marine Biology 132:535-546.

Grigg, R.W. and K.Y. Tanoue. 1984. Proceedings of the second symposium on resource investigations in the Northwestern Hawaiian Islands, Honolulu, Hawaii. UNIHI-SEAGRANT_MR_80-04.

Grigg R.W., J. Polovina, A.M. Friedlander, and S.O. Rohmann. 2008. Biology of Coral Reefs in the Northwestern Hawaiian Islands. pp. 573-594. In: B.M. Riegel and R.E. Dodge (eds.). Coral Reefs of the USA. Springer Scientific and Business Media.

Hobson, L.A. 1980. Primary productivity of the North Pacific Ocean: a review. In: Salmonid ecosystems of the North Pacific. Oregon State University Press, Corvallis, 231-246.

Hourigan, T.F. and E.S. Reese. 1987. Mid-ocean isolation and the evolution of Hawaiian reef fishes. Trends in Ecology and Evolution, 2: 187-191.

Jones, R.S. 1968. Ecological relationships in Hawaiian and Johnston Island Acanthuridae (Surgeonfishes). Micronesica 4:309-361.

Kawamoto, K. and D. Gonzales. 2005. Summary of bottomfish landings in the Hawaiian Island Archipelago, 1996-2004. Pacific Islands Fisheries Science Center Internal Report IR-05-023. 9 pp.

Kelley, C. 2000. Characterizing deepwater habitats in Hawaii using multibeam sonar and submersible technologies. Abstract. 9th International Coral Reef Symposium, Bali, Indonesia. October, 2000. 166 pp.

Kelley, C. and W. Ikehara. 2006. The impacts of bottomfishing on Raita and West St. Rogatien Banks in the Northwestern Hawaiian Islands. Atoll Res. Bull. 543: 305-318.

Kelley, C., R. Moffitt, and J. R. Smith. 2006. Description of bottomfish essential fish habitat on four banks in the Northwestern Hawaiian Islands. Atoll Res. Bull. 543: 319-332.

Kobayashi, D.R. 2006. Colonization of the Hawaiian Archipelago via Johnston Atoll: a characterization of oceanographic transport corridors for pelagic larvae using computer simulation. Coral Reefs 25: 407-417.

Kobayashi, D.R. In review. Larval retention versus larval subsidy: Marine connectivity patterns within and around the Hawaiian Archipelago" Mar. Ecol. Prog. Ser.

Leis, J.M. 1987. Review of the early life history of tropical groupers (Serranidae) and snappers (Lutjanidae). Pp. 189-237. In (J.J. Polovina and S. Ralston, eds.), Tropical Snappers and Groupers: Biology and Fisheries Management. Westview Press, Boulder and London.

Leis, J.M. 1993. The pelagic stage of reef fishes: the larval biology of coral reef fishes. Pp. 183-23. In: (PF Sale, ed), The Ecology of Fishes on Coral Reefs. Academic Press, San Diego.

Maragos, J.E. and P.L. Jokiel. 1986. Reef corals of Johnston Atoll: one of the world's most isolated reefs. Coral Reefs 4: 141-150.

Meyer, C.G., K.N. Holland, and Y.P. Papastamatiou. 2007b. Seasonal and diel movements of giant trevally (*Caranx ignobilis*) at remote Hawaiian atolls: implications for the design of Marine Protected Areas. Marine Ecology Progress Series. 333: 13-25.

Meyer, C.G., Y.P. Papastamatiou, and K.N. Holland. 2007a. Seasonal, diel and tidal movements of green jobfish (*Aprion virescens*, Lutjanidae) at remote Hawaiian atolls: Implications for Marine Protected Area design. Marine Biology. 151: 2133-2143.

Moseman, S.M., L.A. Levin, C. Currin, and C. Forder. 2004. Colonization, succession, and nutrition of macrobenthic assemblages in a restored wetland at Tijuana Estuary, California. Estuarine, Coastal and Shelf Science 60: 755-770.

NOAA. 2006. Draft supplemental environmental impact statement. Bottomfish and seamount groundfish fisheries of the western Pacific region. Measures to end bottomfish overfishing in the Hawaiian archipelago. NOAA, NMFS, Pacific Islands region and Western Pacific Regional Fishery Management Council. Honolulu, Hawaii.

Oda, D.K. and J.D. Parrish. 1981. Ecology of commercial snappers and groupers introduced to Hawaiian Reefs. Pp:59-67. In: Proc. 4th Int Coral Reef Symp 1.

Okamoto, H. and B. Kanenaka. 1984. Preliminary report on the neasrshore fishery resource assessemnt of the Northwestern Hawaiian Islands, 1977-82. Pp. 123-14. In: (R.W. Grigg and K.Y. Tanoue, eds.), Proc 2nd Symp Resource Invest NWHI, Vol 1. Sea Grant Misc Rep UNIHI-SEAGRANT-MR-84-01J.

Papastamatiou, Y.P., B.M. Weatherbee, C.G. Lowe, and G. L. Lowe. 2006. Distribution and diet of four species of carcharhinid shark in the Hawaiian Islands: evidence for resource portioning and competitive exclusion. Mar. Ecol. Prog. Ser. 320: 239-251.

Parke, M. 2007. Linking Hawaii fisherman reported commercial bottomfish catch data to potential bottomfish habitat and proposed restricted fishing areas using GIS and spatial analysis. NOAA Technical Memo. NMFS-PIFSC-11.

Parrish, F. A. and Borland, R.C. 2004. Habitat and reef-fish assemblages of banks in Northwestern Hawaiian Islands. Marine Biology 144: 1065-1073. DOI 10.1007/s00227-003-1288-0.

Parrish, F. A., G. J. Marshall, C.L. Littnan, M. Heithaus, S. Canja, B. L. Becker, R. C. Braun, and G. A. Antonelis. 2005. Foraging of juvenile monk seals at French Frigate Shoals, Hawaii. Marine Mammal Science 21(1):93-107.

Parrish, F. A., K. Abernathy, G. J. Marshall, B. M. Buhleier, 2002. Hawaiian monk seals (*Monachus schauinslandi*) foraging in deepwater coral beds. Mar. Mamm. Sci. 18:244-258.

Parrish, J., L. Taylor, M. DeCrosta, S. Feldkamp, S. Sanderson, and C. Sorden. 1980. Trophic studies of shallow-water fish communities in the Northwestern Hawaiian Islands. Pp. 175-188 in (RW Grigg and RT Pfund, eds) Proc Symp Status Resource Invest NWH, April 24-25, 1980. U HI Honolulu Sea Grant Misc Rep UNIHI-SEAGRANT-MR-80-04.

Parrish, F. A., M. P. Craig, T. J. Ragen, G. J. Marshall, and B. M. Buhleier. 2000. Identifying diurnal foraging habitat of endangered Hawaiian monk seals using a seal-mounted video camera. Mar. Mamm. Sci. 16:392-412.

Polovina, J.J. 1984. Model of a coral reef ecosystem. I. the ECOPATH model and its application to French Frigate Shoals. Coral Reefs 3: 1-11.

Ramon, M., P. Nelson, E. DeMartini, W. Walsh, and G. Bernardi. 2008. Phylogeography, historical demography, and the role of post-settlement ecology in two Hawaiian damselfish species. Marine Biology 153: 1207-1217.

Randall, J.E. 1987. Introductions of marine fishes to the Hwaiian Islands. Bull Mar Sci 41: 490-502.

Randall, J.E., J.L. Earle, R.L. Pyle, J.D. Parrish, and T. Hayes. 1993. Annotated checklist of the fishes of Midway Atoll, Northwestern Hawaiian islands. Pac Sci 47: 356-400.

Rivera, M., C. Kelley, and G. Roderick, 2004. Subtle population genetic structure in the Hawaiian Grouper, *Epinephelus quernus* as revealed by mitochondrial DNA analyses. Biological Journal of the Linnean Society 81: 449-468.

Rocha, L.A., M.T. Craig, and B.W. Bowen. 2007. Phylogeography and the conservation genetics of coral reef fishes. Coral Reefs Invited Review 26: 501-512.

Schultz, J.K., R.L. Pyle, E. DeMartini, and B.W. Bowen. 2007. Genetic connectivity among color morphs and Pacific Archipelagos for the flame angelfish, *Centropyge loriculus*. Mar. Biol. 151:167-175.
Shanks, A.L. 2003. Propagule dispersal distance and the size and spacing of marine reserves. Ecol. Applic. 13(1) Suppl.:S159-S169.

Skillings, D., C.E. Bird, and R.J. Toonen. In prep. Using the sea cucumber Holothuria atra to test Hawaiian connectivity hypotheses. Journal of Biogeography.

Sladek Nowles, J. and A. M. Friedlander. 2004. Research priorities and techniques. Pp. 187-233 In: Marine Reserves; their science, design and use (J. Sobel and C. Dahlgren, eds.). Island Press. Washington, DC.
Treml, E.A., P.N. Halpin, D.L. Urban, and L.F. Pratson. 2008. Modeling population connectivity by ocean currents, a graph-theoretic approach for marine conservation. Landscape Ecology 23: 19-36.

Valles, H., S. Sponaugle, and H.A. Oxenford. 2001. Larval supply to a marine reserve and adjacent fished area in the Soufriere Marine Management Area, St Lucia, West Indies. J Fish Biol 59: 157–177.

Victor, B.C. 1993. Settlement strategies and biogeography of reef fishes. Pp. 231-260. In: (P.F. Sale, ed), The Ecology of Fishes on Coral Reefs. Academic Press, San Diego.

WPRFMC (Western Pacific Regional Fisheries Management Council). 2004. Bottomfish and seamount grounffish fisheries of the Western Pacific region: 2002 Annual Report. Western Pacific Regional Fisheries Management Council, Honolulu, Hawaii.

PERSONAL COMMUNICATIONS

Craig, M.T. Hawaii Institute of Marine Biology, Kaneohe, HI, USA.

WEBSITES

University of British Columbia (UBC), Fisheries Centre. http://www.ecopath.org

Management Concerns and Responsibilities

Kaylene E. Keller[1], Angela D. Anders[2], Ann Mooney[1], Randall Kosaki[1], Malia Chow[1] and Mark Monaco[3]

INTRODUCTION

Increasing pressures on the world's ocean resources in the recent decades has heightened the need for protecting marine resources. Marine Protected Areas (MPA) are an essential tool for achieving marine ecosystem-based management. MPAs in the Pacific, such as Papahanaumokuakea Marine National Monument, the Australia's Great Barrier Reef Marine Park and the Phoenix Islands Protected Area in Kiribati lead the world in protecting large-scale marine ecosystems. Each of these MPAs conserves vast contiguous areas of ecosystems ranging from shallow water coral reefs to deep water communities.

The Papahanaumokuakea Marine National Monument (Monument) is one of the largest and most unique MPAs in the world. The Monument contains relatively pristine ecosystems and cultural resources minimally affected by human activities. In seeking to preserve and protect these attributes, Monument managers identified the following mission: "Carry out seamless integrated management to ensure ecological integrity and achieve strong, long-term protection and perpetuation of the NWHI ecosystems, Native Hawaiian culture, and heritage resources for the current and future generations" (Papahanaumokuakea Marine National Monument, 2008).

Striving to achieve this far-reaching mission creates unique opportunities and challenges for Monument managers. These opportunities include the potential to manage complete ecosystems with few anthropogenic inputs and working toward restoring components of the ecosystems that have been modified. Challenges revolve around the remote and vast nature of the Monument, and include threats local to global and internal and external to the Monument. This chapter focuses on management of the Monument. This includes:

- Management structure;
- Management of protected marine species within the Monument;
- Management of greatest potential threats to the marine resources across the region; and
- Management of human activities.

BACKGROUND

Management Structure

On June 15, 2006, President George W. Bush issued Presidential Proclamation 8031 (Proclamation) establishing the NWHI Marine National Monument under the authority of the Antiquities Act of 1906 (16 U.S.C. 431). It was subsequently renamed the Papahanaumokuakea Marine National Monument. The Monument includes a number of preexisting federal conservation areas: the NWHI Coral Reef Ecosystem Reserve, managed by the Department of Commerce through the National Oceanographic and Atmospheric Administration (NOAA) Office of National Marine Sanctuaries; Midway Atoll National Wildlife Refuge, Hawaiian Islands National Wildlife Refuge, and Battle of Midway National Memorial, managed by the Department of the Interior through the United States Fish and Wildlife Service (USFWS). These areas remain in place within the Monument, subject to their applicable laws and regulations in addition to the provisions of the Proclamation.

The NWHI also include state of Hawaii lands and waters, managed by the Hawaii Department of Land and Natural Resources (DLNR) as the NWHI Marine Refuge and the State Seabird Sanctuary at Kure Atoll. These areas also remain in place and are subject to their applicable laws and regulations.

---

1. NOAA/NOS/ONMS/Papahanaumokuakea Marine National Monument
2. Clancy Environmental Consultants, Inc.
3. NOAA/NOS/NCCOS/CCMA Biogeography Branch

The organizational structure for the Monument consists of:

- Three Co-Trustees-- Department of Commerce, Department of the Interior and the State of Hawaii-- responsible for the management of the Monument. The Co-Trustee agencies have developed a joint management plan that will guide management of the Monument for the next 15 years;
- A Senior Executive Board composed of a designated senior policy official from each Co-Trustee agency that is directly responsible for providing oversight and guidance for management of the Monument;
- A Monument Management Board composed of representatives from the federal and state agency offices that carry out the day-to-day management and coordination of Monument activities; and
-
- An Interagency Coordinating Committee representing other state and federal agencies as appropriate to assist in the implementation of Monument management activities.

Management Zones

Monument regulations define three types of marine zones within the Monument (Figure 10.1):

1. Special Preservation Areas: These are discrete, biologically important areas of the Monument where resource harvest and almost all forms of discharge are prohibited;
2. Ecological Reserves: These areas consist of contiguous, diverse habitats that provide natural spawning, nursery, and permanent residence areas. Resource extraction is highly restricted within Ecological Reserves; and
3. Midway Atoll Special Management Area (SMA): Recreational activities in the Monument are restricted to the Midway Atoll SMA.

Zoning not only provides protection to highly sensitive habitats, it also protects the ecological linkages between these habitats. Each zone addresses a number of factors including the protection of habitat and foraging areas of threatened and endangered species; the inclusion of a representative range of the diverse array of marine

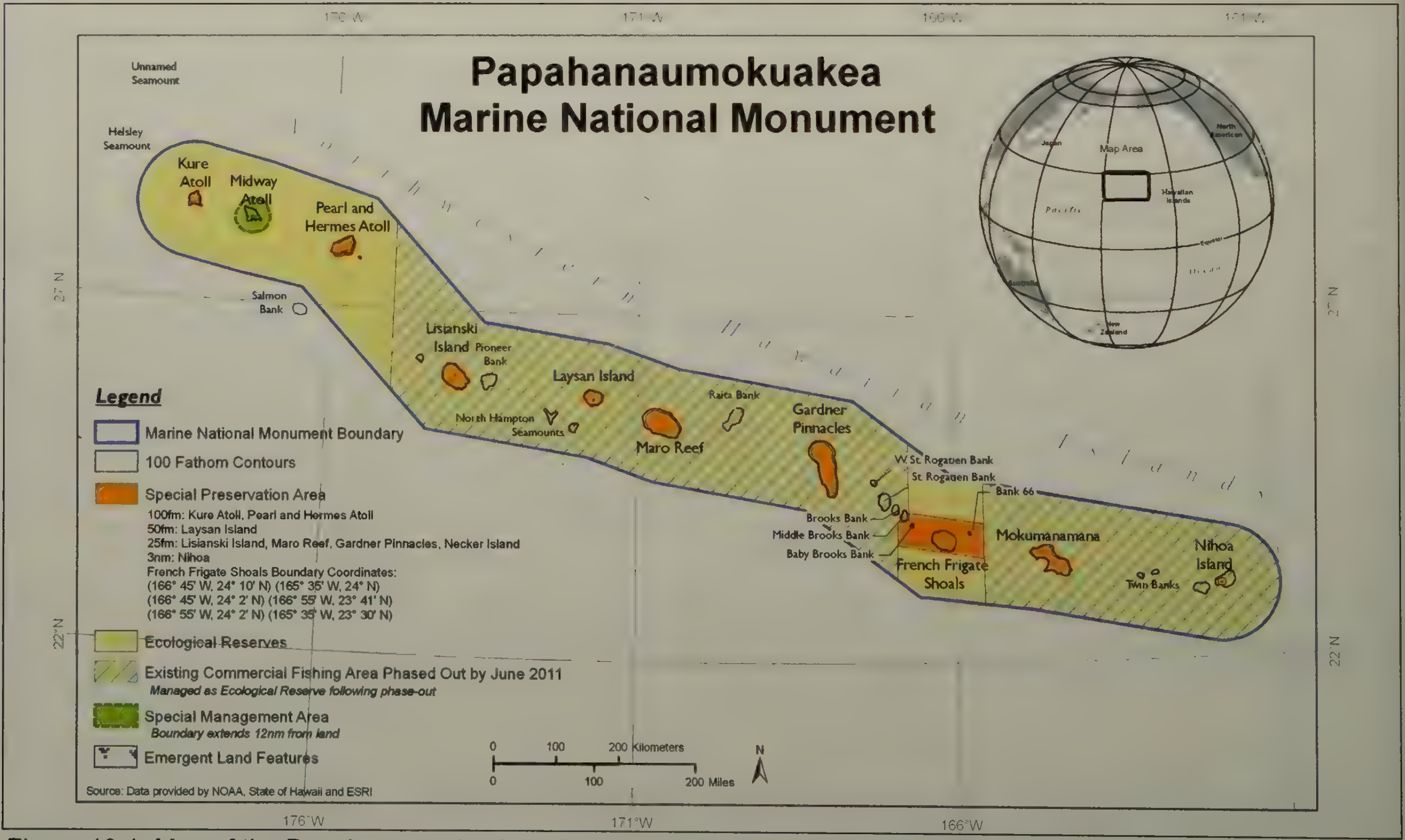


Figure 10.1. Map of the Papahanaumokuakea Marine National Monument and zones. Map: PMNM.

habitats, including shallow coral reef environments, as well as deepwater slopes, banks and seamounts; and finally, the minimization of risks associated with specific activities such as fishing and recreational activities. As of June 2011 all commercial fishing will be prohibited within the Monument.

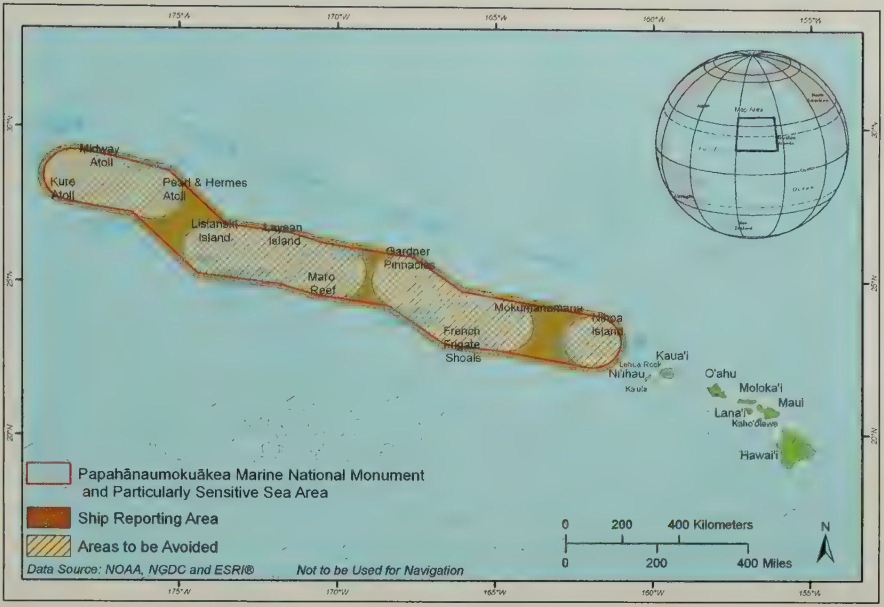


Figure 10.2. PSSA, Areas to be Avoided (ATBA) and Ship Reporting Boundaries around the Papahanaumokuakea Marine National Monument.

In addition to the designation of the Monument management zones, in 2007 the Monument was designated "in principle" as a Particularly Sensitive Sea Area (PSSA) by the International Maritime Organization (IMO), a Specialized Agency of the United Nations (Figure 10.2). The designation puts into effect internationally recognized measures designed to protect marine resources of ecological or cultural significance from damage by ships while helping keep mariners safe. PSSA designation augments domestic protective measures by alerting international mariners to exercise extreme caution when navigating through the area. A U.S. proposal for PSSA designation was submitted in April 2007 for consideration at the IMO's Marine Environment Protection Committee meeting with the final designation made in April 2008. PSSA designation has been granted to only 10 marine areas globally, including the marine areas around the Florida Keys, the Great Barrier Reef and the Galapagos Islands. The PSSA area is coterminous with the Monument boundary.

In addition to alerting international mariners to exercise extreme caution when in the area, as part of the PSSA designation process, the IMO's Maritime Safety Committee adopted the U.S proposals for the associated protective measures (APMs) of: (1) the expansion and amendment of the six existing recommendatory Areas to be Avoided (ATBAs) in the area, which would enlarge the class of vessels to which they apply and augment the geographic scope of these areas, as well as add new ATBAs around Kure and Midway atolls; and (2) the establishment of a ship reporting system for vessels transiting the Monument, which is mandatory for ships 300 gross tons or greater entering or departing a U.S. port or place and recommendatory for other ships. These APMs were implemented in May 2008.

WORLD HERITAGE NOMINATION

The unique habitats and ecosystems within the Monument are of great importance to local, regional and global marine biodiversity (Figure 10.3). The Monument contains some of the world's most significant marine and terrestrial ecosystems and areas of cultural significance, and is one of the world's largest protected marine areas. It also serves as an example of ongoing geological processes and biological evolution. The volcanic rocks, large atolls of sand and coral, and islets surrounded by reefs provide unique habitats for endemic and rare species of animals and plants. These features are of universal value from scientific, conservation, cultural and aesthetic perspectives. This relatively pristine region contrasts sharply with most insular and marine ecosystems, which are more severely affected by human activities and populations around the world.

In January 2008, Papahanaumokuakea was selected by the Secretary of the Interior to be included as a candidate for the U.S. Tentative List for nomination as a World Heritage mixed site due to its exceptional natural and cultural importance. World Heritage is the designation for places on earth that are of outstanding universal value to humanity and as such, have been inscribed on the World Heritage List to be protected for future generations to appreciate and enjoy. In early 2009, the U.S. put forth a full nomination package to the World Heritage Centre to have the Monument added to the World Heritage List. The Monument was recommended for consideration as a World Heritage Mixed Site. The reasons for listing the Monument include:

- The string of islands comprises a classic, important and unparalleled example of later stages of island and atoll evolution. The archipelago has provided some of the most compelling confirmation of current theories of global plate tectonic movements;
- Papahanaumokuakea is a spectacular example of evolution in isolation, which results in enhanced speciation and a phenomenally high degree of endemism in both marine and terrestrial flora and fauna. The coral reef ecosystems of Papahanaumokuakea also represent on of the worlds's last apex predator dominated ecosystems, a community structure characteristic of coral reefs prior to significant human exploitation; and
- The region is home to, and a crucial refuge for, many endangered, threatened, and endemic species, including critically endangered marine mammal, bird, and plant species for whom it is the last or only refuge anywhere on earth. Papahanaumokuakea is also the largest tropical seabird rookery in the world.

Figure 10.3. The variety of ecosystems within the Monument have been recognized for their uniqueness and importance to global marine biodiversity. Photos: J. Maragos.

Remote, uninhabited and relatively pristine in comparison to other marine ecosystems in the world, the Monument has the potential to serve as one of the few reference sights for monitoring and deciphering short-term and long-term responses to local, regional, and global environmental and anthropogenic stressors. The Monument is one of the few regions on Earth where monitoring and research activities can be conducted in the virtual absence of local human habitation. In comparison, most reef systems in the coastal regions of the world are adjacent to human population centers, where vessel traffic, overharvesting, sedimentation, habitat destruction, and other human actions have altered the terrestrial and adjacent marine environments. Ongoing research, monitoring, habitat restoration and conservation management of the insular and marine ecosystems in the NWHI will continue to provide significant insights that will benefit management interventions not only for the NWHI, but for insular and marine ecosystems around the world.

MANAGEMENT OF PROTECTED SPECIES

The NWHI provides habitat for a wide variety of species including species specifically protected by federal acts and state statutes. Three federal acts, as well as multiple state statutes, provide protections for specific species in the NWHI. The federal acts are the Endangered Species Act (ESA), the Marine Mammal Protection Act (MMPA) and the Migratory Bird Treaty Act (MBTA). The ESA of 1973 provides for the conservation of species at risk of extinction throughout all or a significant portion of their range, and the conservation of the ecosystems on which they depend. The state of Hawaii has adopted specific criteria for indigenous species to be listed as threatened or endangered, as codified in chapter 195D-4, Hawaii Revised Statutes (HRS), as well as chapter 183D, HRS Wildlife, and chapter 125, Wildlife Sanctuaries, Hawaii Administrative Rules Title 13. The MMPA provides protection and conservation of all marine mammals whether or not listed under the ESA. The MBTA is a domestic law that implements the United States' commitment to four international conventions (with Canada, Japan, Mexico and Russia) for the protection of shared migratory bird resources. All migratory birds and their parts (including eggs, nests and feathers) are fully protected.

The Monument provides habitat for many protected marine species including the Hawaiian monk seal, five cetacean species, five marine turtles and five bird species (Figure 10.4).

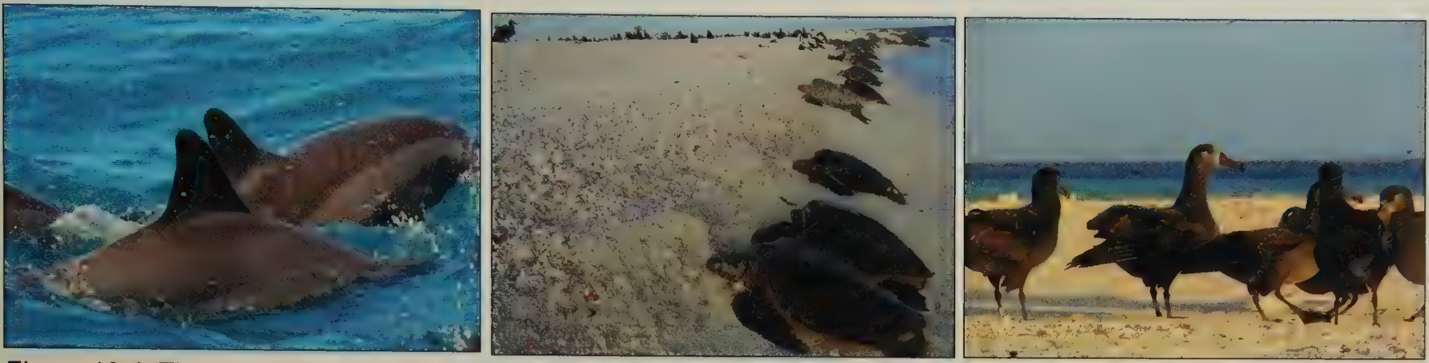


Figure 10.4. The various ecosystems within the Monument are inhabited by of protected species, including marine mammals, marine turtles and seabirds. Photos: J. Watt (right), T. Summers (center) and USFWS (left).

Hawaiian Monk Seal

The Hawaiian monk seal (*Monachus shauinslandi*) is in crisis. The population is in a decline that has lasted 20 years, and today only about 1,200 monk seals remain. Modeling predicts that the species' population will fall below 1,000 animals by the year 2012. Actions to date have not been sufficient to result in a recovering population. Most of the population of Hawaiian monk seals breed and forage inside the Monument boundaries. NOAA's National Marine Fisheries Service (NMFS) is the primary federal agency responsible for the management of the Hawaiian monk seal and has identified the recovery of this species as the number one priority, based on the high magnitude of threats, the high recovery potential, and the potential for economic conflicts while implementing recovery actions. NMFS recently updated its Hawaiian monk seal recovery plan and has detailed several key actions required to address current and potential threats to the recovery and survival of this critically endangered species (NMFS, 2007). To advance these efforts, the Monument management board is pursuing several key strategies as identified in its management plan in support of monk seal recovery efforts (PMNM, 2008).

Cetaceans

Sightings and acoustic recordings of baleen whales, as well as toothed whales and dolphins have been documented throughout the Monument. Five species of baleen whales listed as "endangered" under the ESA and as "depleted" under the MMPA have been sighted or heard in the Monument area. In addition to these five, the endangered sperm whale (*Physeter macrocephalus*) and at least 18 other non-ESA listed species are found in the Monument (see the Marine Protected Species chapter for more information). It has now been documented that humpback whales (*Megapera novaeangliae*) are calving in the eastern portion of the Monument (Johnston et al., 2007). Recovery actions for this listed species are summarized in the final recovery plan for the humpback whale (NOAA Fisheries, 1991). Draft recovery plans are available for the fin whale and sperm whale (NOAA Fisheries, 2006a, 2006b), and a final plan is available for the recovery of the blue whale (NOAA Fisheries, 1998).

Marine Turtles

The Hawaiian green turtle (*Chelonia mydas*), hawksbill (*Eretmochelys imbricate*), loggerhead (*Caretta caretta*), and leatherback (*Dermochelys coriacea*) turtles are known to occur within the Monument boundaries. While there are no records of the endangered olive ridley (*Lepidochelys olivacea*) within Monument waters, their wide distribution throughout the tropical Pacific makes it plausible that they also occur there Green and loggerhead sea turtles are listed as threatened species; the hawksbill and leatherback turtles are classified as endangered species. Recovery plans and five-year reviews jointly published in 2007 are in place for each of these species in the Pacific (NOAA Fisheries and USFWS, 1998a; 1998b; 1998c; 1998d; 1998e, 2007). Sea turtle population declines have occurred across the Pacific due to nesting habitat loss, fishery interactions and the harvest of eggs and turtles for commercial and subsistence purposes. About 90% of the green turtles in the Hawaiian Islands nest in the NWHI, the majority on a few islets at French Frigate Shoals (Balazs and Chaloupka, 2004). Green turtle populations have steadily increased in Hawaiian waters since the species was added to the list of threatened species in 1978.

Seabirds

Five endangered bird species in the NWHI are protected under the ESA. The only seabird occurring in the NWHI listed under the ESA is the Short-tailed Albatross (*P. albatrus*). The other four ESA listed endangered bird species are the Laysan Duck, Laysan Finch, Nihoa Finch and Nihoa Millerbird.

The Short-tailed Albatross breeds primarily on Torishima, an island owned and administered by Japan. The Short-tailed Albatross was first observed at Midway Atoll between 1936 and 1941. Since then, one to three individuals have been observed every year in the NWHI, primarily on islands in the northwestern half of the Monument. Although short-tailed albatrosses do not currently nest in the NWHI, a small number of adult birds conduct breeding displays each year at Midway Atoll. The Short-tailed Albatross Draft Recovery Plan provides recommendations for ways in which Monument staff can facilitate recovery of this species (USFWS, 2005).

The Laysan Albatross (*P. immutabilis*) and the Black-footed Albatross (*P. nigripes*) are both considered endangered by International Union for Conservation of Nature (IUCN) and BirdLife International. Both species breed in the NWHI and also forage outside of the Monument. A Conservation Action Plan for both Black-footed Albatross and Laysan Albatross (Naughton et al., 2007) has been developed to provide managers with a framework for the conservation of both species. In addition to the three albatross species that occur in the Monument, another 18 species of seabirds and five species of shorebirds that regularly breed and overwinter, respectively, in the NWHI, are fully protected under the MBTA. The Monument Management Plan (MMP) includes activities to protect and enhance seabird and shorebird habitat and to minimize impacts of habitat destruction, contaminants and fisheries interactions

Management and conservation of migratory species such as cetaceans, marine turtles and seabirds will require coordination with international partners and conservations organizations outside of the Monument.

MANAGEMENT OF THREATS TO THE ECOSYSTEM

Anthropogenic activities impact oceans worldwide (Halpern et al., 2008). On a global scale, the highest ranking threats to coral reefs were identified as sedimentation, coastal development, trampling and nutrient inputs (Halpern et al., 2007). At a regional scale, these threats vary by location. The remoteness of the Monument as well as its limited emergent land results in a different suite of identified ecosystem threats.

The Monument is affected by past changes to the ecosystem as well as current on-going threats. The emergent land areas and potentially some near shore waters continue to be affected by contaminants left over from military use of the islands. During World War II, large scale modifications such as channelization were made to the environment which changed the flow of water within the atolls and continues to impact the local ecosystem. In addition, marine species that also use emergent land such as seabirds are negatively impacted by invasive terrestrial species and other terrestrial based threats such as contaminants. It is important for mangers to be able to identify the potential threats and evaluate the impact of the threat to the overall functioning of the ecosystem at a local scale as well as a regional scale.

In a recent threat analysis of the NWHI region, 24 potential threats were analyzed based on vulnerability factors and order of magnitude of the threat (Selkoe et al., 2008; Table 10.1). The analysis was focused on threats to the marine environment across the NWHI region. A systematic and quantitative method was used to collect and synthesize expert opinion on the ecological effects of these potential anthropogenic threats to the region.

The following discussion of threats to the Monument focuses on the top four threats identified across ecozones for the region by expert opinion. These threats are:

1. Climate change
2. Marine debris/ghost fishing
3. Alien species
4. Ship groundings

Table 10.1. Potential threats analyzed by Selkoe et al., 2008. Source: Selkoe et al., 2008.

THREAT	EXPLANATION
Alien species	Includes only populations that have established, not single sightings
Anchor damage	Includes large anchors in deepwater and small anchors of tender boats
Aquarium collecting	Primarily aquarium trade activities, only one example of legal event to date
Bottomfishing	An ongoing fishery for a suite of deepwater snapper and grouper using hydraulic handlines >100 fathoms depth outside three nautical miles. Boats also troll in transit, impacting pelagic fish and birds
Coastal engineering	The lingering impacts of past dredging, seawalls and pier construction, and ongoing maintenance activities, primarily at Midway and French Frigate Shoals
Diver impacts	Includes diving for any purpose (but it primarily occurs for research); may cause disturbance to animals, damage to corals, potential for inter-site transfer of micro-organisms
Ghost fishing	A subcategory of marine debris - mostly discarded monofilament and rope nets and some lost lobster traps that ensnare and drown animals and smother reefs
Increasing UV radiation	Increased ultraviolet radiation from the anthropogenic thinning of the ozone layer
Indigenous fishing	Fishing by native Hawaiians for consumption - this potential activity is likely focused on southeast end of NWHI
Chemical contamination	The leeching of chemical waste from past and ongoing military activities and habitation, primarily at Midway and French Frigate Shoals
Lobster fishing	Lobster fisheries were halted in 2000 due to population collapses. Only lingering impacts were considered -- there has been little rebound of lobster to date, potentially impacting lobster predator populations (e.g. monk seals)
Marine debris	All types of man-made materials (including plastics and derelict fishing gear) that may break corals, entangle animals, are ingested by animals and accumulate on beaches
Recreation	Any recreational activities not covered by fishing and diving, such as boating, water sports, and wildlife viewing.
Pelagic fishing	Pelagic fishing is banned in NWHI waters but biological connection to the wider Pacific where longlining and net fishing is intense may impact NWHI species which forage in the Pacific, both as bycatch and because the tuna on which some birds depend for foraging are being depleted
Research installations	Installation of equipment or otherwise modifying benthos, or disturbing animals
Research wildlife sacrifice	Any lethal sampling of organisms for research activities
Sea level rise	Increased sea level from the anthropogenic warming of the planet. May alter habitat availability and stress populations of depth-dependent species like corals
Sea temperature rise	Increased temperature from the anthropogenic warming of the atmosphere. A suspected cause of increases in coral bleaching and coral disease, among other potential effects
Sea water acidification	Decreased sea water pH due to the anthropogenic carbon loading of the atmosphere
Ship groundings	Includes the damage and disturbance from grounding, fuel spill, debris, cyanobacteria inoculation and debris removal.
Ship pollution	Includes the discharge of bilge water, sewage, spilled fuel, trash and noise and light pollution. Includes all types of vessels (fishing, research, shipping, tourist).
Sport fishing	Most relevant to southeast end of chain, the lingering impacts of the abated catch-and-release operation at Midway and Pearl and Hermes, and ongoing trolling during ship transit
Trampling damage	Walking on beaches, intertidal, emergent land and reef flats not associated with diving
Vessel strikes	When a small or large vessel hits benthic communities or large mobile animals while in transit, without grounding

Managers recognize the need to evaluate threats based upon the source and impact of the identified hazard. If a threat occurs within the management boundary, managers have more opportunity to successfully mitigate the threat. Threats generated outside of the management boundary still require a response, but they are often more difficult to prevent. Of the top four identified threats to the Monument, climate change and marine debris originate outside the boundaries of the Monument. Alien species establishment and ship groundings are considered locally-based threats that occur within the Monument boundaries.

Climate change factors are already affecting the NWHI ecosystem and will have a widespread impact. Sea-level rise is already impacting available habitat for species such as the Hawaiian monk seal, green turtle and the seabirds. The impact from sea surface temperature (SST) changes will be seen throughout the ecosystem including coral bleaching and potential impacts to prey species for seabirds and other predators. Marine debris was also identified threat from outside the Monument that will impact many different ecozones.

Alien species and ship groundings are identified as high local threats because they have a potentially large impact on ecosystem function and long recovery times. To date, the threat of alien species may not be highly significant in marine areas within the NWHI (i.e., 13 marine alien species currently known to occur within the Monument) but the potential impact from an introduction could be widespread. There is always the potential for ship groundings but emergency response plans to minimize the impacts of the groundings are under development

Selkoe et al. (2008) evaluated, eight different ecozones (Table 10.2). A finer-scale threat analysis can occur by examining the ecozones and assessing how a threat may impact each specific area. The inner and outer reef zones were identified as the most vulnerable. Emergent land was considered vulnerable because of sea level rise and the potential loss of habitat. The shallow water ecozones were more vulnerable to extra-boundary threats than local threats. Many of these top threats are difficult for local managers to control because they arise from activities outside the Monument boundaries, indicating that additional work is needed to preserve the NWHI despite its highly protected status. The analysis indicates where interagency cooperation in removing and mitigating threats should be focused (Selkoe et al., 2008)

Table 10.2. Ecozones evaluated in the threat analysis. Source: Selkoe et al., 2008.

ECOZONE	DESCRIPTION	DISTRIBUTION
Terrestrial	Interior land distinct from the littoral zone	Kure, Midway, Lisianski, Lysan, Mokumanamana and Nihoa
Rocky Intertidal	Solid substrate at intertidal depth composed of basalt rock	Gardner Pinnacles, La Perouse Pinnacle (French Frigate Shoals), Mokumanamana and Nihoa
Sandy Beach	Intertidal beach and adjacent shallows with soft benthos	Kure, Midway, Pearl and Hermes, French Frigate Shoals, Lisianski, Laysan, and Nihoa
Algal Beds	Primarily Halimeda beds in lagoons and deeper terraces, but also small stands of endemic seagrass at Midway	Kure, Midway, Pearl and Hermes,French Frigate Shoals, Lisianski, Laysan, Mokumanamana and Nihoa
Inner Reef	Refers to shallow, mostly protected reef areas (lagoonal, back, reticulated or patch reefs)	Kure, Midway, Pearl and Hermes, Lisianski, Neva Shoals, Laysan, Maro, and French Frigate Shoals
Outer Reef	Exposed seaward reefs from the crest down to the slope less than 30 m depth	Most NWHI locations where depth is <30 m
Deep Reef/ Banks	Deep reef is designated >30 m depth. Banks are sites of high relief benthos in deep waters with rich fish communities, with or without reef builders	There are approximately 30 deep banks in the NWHI. Deep reef is usually found adjacent to any shallow reef area.
Pelagic Waters	The entire water column, from surface to depth, outside of lagoon and shallow reef environments	Makes up the majority of NWHI habitat.

Climate Change

Sea level rise, changing storm intensity and frequency, sea surface temperature (SST) rise and acidification are components of climate change most likely to affect the Monument. Evidence of sea level rise has already begun to adversely affect the available terrestrial habitat and models predict that sea level will continue to rise. SST is monitored via satellite in addition to using buoys at several locations throughout the NWHI, resulting in a long-term temperature time series for Midway Atoll (Jokiel and Brown, 2004). Elevated SST has already impacted corals as indicated by recent coral bleaching events in the Monument (see Coral Bleaching for more details). With regards to ocean acidification, the third component of climate change most likely to affect the Monument, staff members are in the process of designing experiments to characterize the carbonate chemistry and establish a baseline for the NWHI.

Sea Level Rise

Global mean sea levels have risen an estimated 3.1 ± 0.7 mm yr^{-1} from 1993-2003, an amount higher than any other 10-year period since 1950 (IPCC, 2007). However sea level rise varies regionally and in order to understand the effects on the ecosystem it must be monitored at the island and atoll scale.

One effect of rising sea level in the NWHI is the loss of habitat. Emergent land in the NWHI is estimated at a total 14 km^2 and the loss of available emergent land will greatly reduce the available habitat for many species. The effect of habitat loss on species that use emergent land features will impact many of the species that are already rare and maybe devastating to those populations that depend on these islands for survival. Marine species that will be impacted by sea level rise include the Hawaiian monk seal, green turtle and several seabird species. In addition there is the potential for further habitat degradation with the release of contaminants contained in landfills and other areas as the islands are eroded or flooded from sea level rise.

Table 10.3. Sea level rise scenarios modeled for French Frigate Shoals, Lisianski Island and Pearl and Hermes Atoll. Source: Baker et al., 2006.

SCENARIO	RISE LEVEL	BASE SEA LEVEL
Scenario 1 - Low	9 cm	Mean Low Water (MLW)
Scenario 2 - Low		Spring Tide
Scenario 3 - Median	48 cm	Mean Low Water (MLW)
Scenario 4 - Median		Spring Tide
Scenario 5 - High	88 cm	Mean Low Water (MLW)
Scenario 6 - High		Spring Tide

Evidence of sea level rise can be clearly observed with the submersion of Whaleskate Island within French Frigate Shoals in the late 1990s (Baker et al., 2006). NOAA Pacific Islands Fisheries Science Center (PIFSC) modeled the potential terrestrial habitat loss from sea level rise using estimated sea level rise values and current elevation data collected in the field. The study included islands within Pearl and Hermes Atoll, Lisianski Island and French Frigate Shoals. Pearl and Hermes Atoll and French Frigate Shoals are both composed of small low lying islets surrounded by a barrier reef, whereas Lisianski Island is a single large, low-lying island (Figure 10.5). Six different scenarios using three sea level rise values and two different tide conditions were evaluated (Table 10.3). The results of the modeling indicate that sea level rise will affect each island group differently. Lisianski Island (the largest and highest island in the analysis), could experience the least amount of impact with only a 5% decrease in area using the highest sea level rise scenario. In contrast, the highest seal level rise scenario for the islets at Pearl and Hermes Atoll and French Frigate shoals range from a 25% loss up to 90% loss (Baker et al., 2006). The estimates produced by the model were based on the assumption that the island shape remains constant and the model did not include erosion factors. Efforts to develop a monitoring system of the changes in the size of the islands are currently underway.

Sea turtles are dependent on terrestrial areas for nesting. Islets in French Frigate Shoals support the majority of the Hawaiian green turtle breeding population. The loss of habitat and the possibility for nesting areas to be flooded during nesting times could have a large impact on the species. In other regions, green turtles have demonstrated intra-specific nest destruction once habitat is lost and nest density becomes high (Bustard and Tognetti, 1969). This behavior may occur among nesting Hawaiian green sea turtles in the Monument if nesting habitat is destroyed.

Impacts to seabirds will vary depending upon the species. Over 90% of Black-footed and Laysan Albatrosses breed in the Monument and the loss of habitat in this area could affect the overall world population. The largest breeding populations of these albatross species occur at Midway Atoll and Laysan Island which were not analyzed in the sea level rise study, but habitat loss is expected to be similar to Lisianski Island because they are both large islands. The predicted decrease in area would not be large, but the species remain vulnerable as the islands represent such a critically important breeding area. Other seabird species may also be potentially impacted by the loss of nesting habitat as the result of climate change.

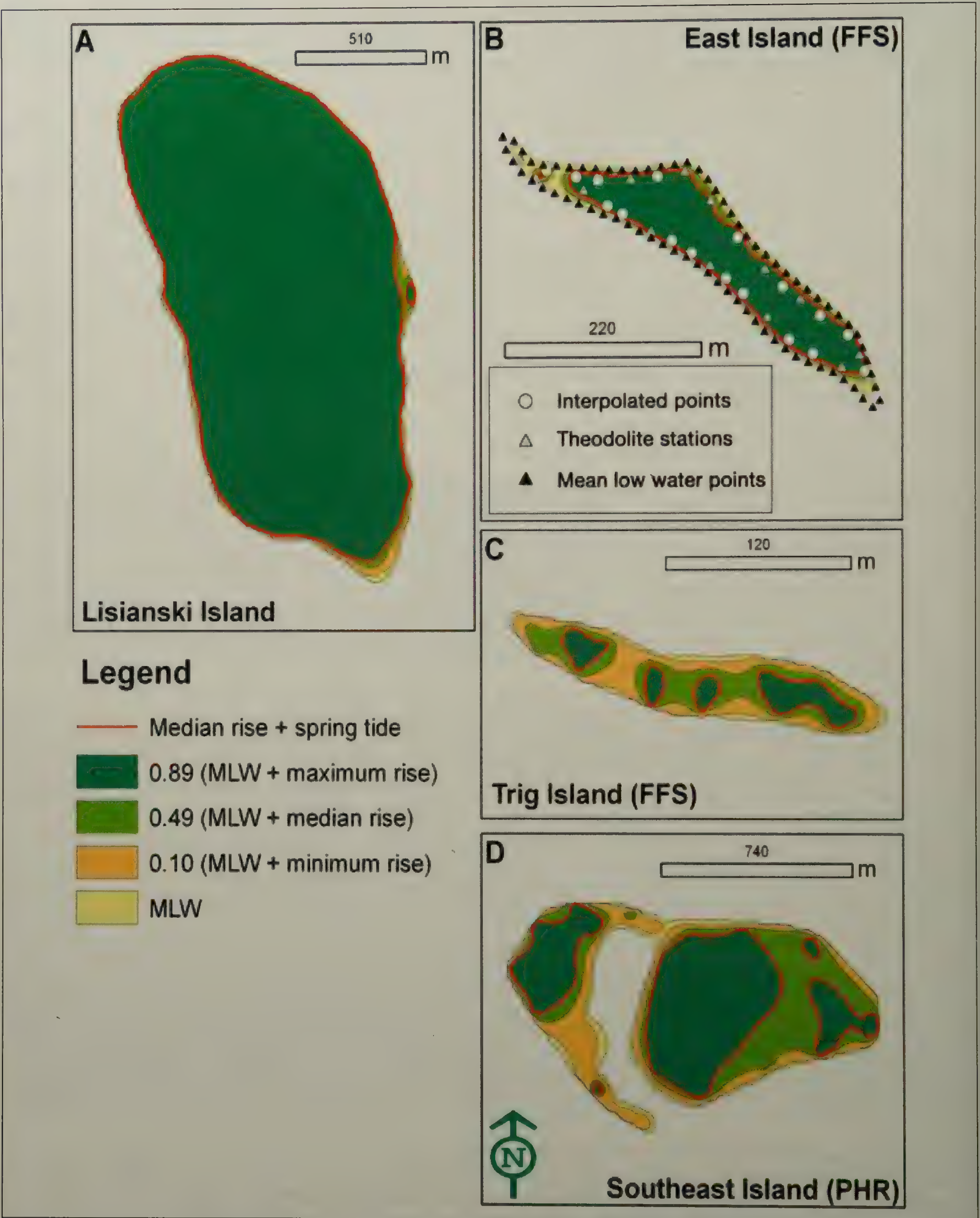


Figure 10.5. Current and projected maps of four NWHI at mean low water (MLW) with minimum (9 cm), median (48 cm) and maximum (88 cm) predicted sea level rise. The median scenario at spring tide is also shown. (A) Lisianski Island; (B) East Island, French Frigate Shoals, showing the measured and interpolated points along the waterline and berm used to create the Triangular Irregular Network (TIN); (C) Trig Island, French Frigate Shoals; (D) Southeast Island, Pearl and Hermes Reef. Source: Baker et al., 2006.

Storm Intensity and Frequency

Global weather patterns appear to be changing and climatologists suggest that the increasing intensity and frequency of storms may be related to modern, anthropogenic influences (IPCC, 2001; Nott, 2003; Nott, 2004; Nott et al., 2007). Studies into storm trends have shown that while SSTs have been rising, the intensity of the storms occurring in this time period has increased (Hoegh-Guldberg, 1999; IPCC, 2001; Hughes, 2003; Webster et al., 2005; IPCC, 2007; NOAA Satellite and Information Service, 2007). While sheer numbers of tropical storms have remained relatively constant, the destructiveness of the cyclones has increased over the past 30 years and hurricanes in the Category 4 and 5 range have nearly doubled since the 1970s (Emanuel, 2005; Webster et al., 2005). If climate patterns follow the projections, storms may continue to increase in intensity over the coming years. As storm intensity increases, the impacts felt by low-lying islands and atolls could prove detrimental to the inhabitants.

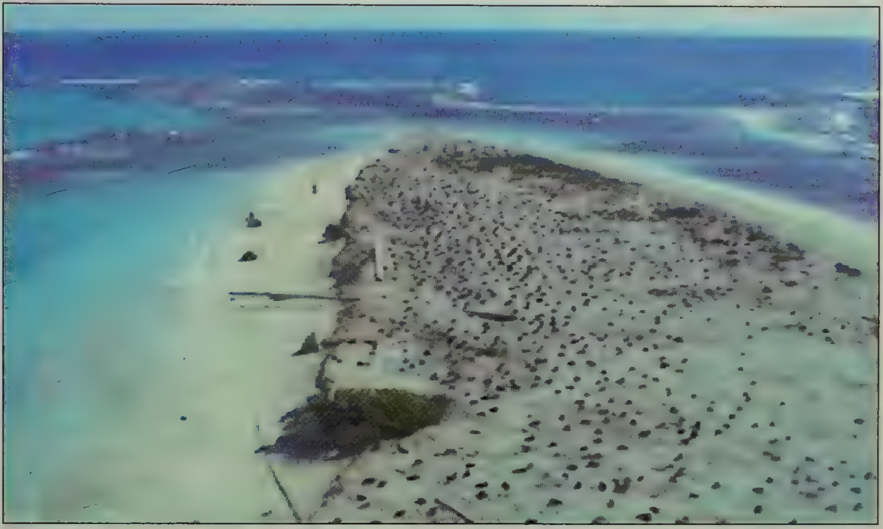


Figure 10.6. *High levels of erosion on East Island just days after highly intense storms passed through the area in December 2008. Photo: PIFSC and G. Balazs.*

The damage from high intensity storms to low lying sand islands was demonstrated in late December 2008 at French Frigate Shoals when high levels of erosion occurred at East Island. Using remote cameras available for monitoring turtle nesting activity scientists at PIFSC were able to evaluate the damage to East Island which included several feet of erosion along the northwest side of the island (G. Balazs pers. comm; Fig 10.6). Monitoring will need to be conducted to evaluate the long-term impact of the erosion event and to determine if accretion will occur to other parts of the island. Researchers active in the NWHI over the past 30 years have observed changes to the size and shape of many of the islands (G. Balazs and J. Maragos, pers. comm.). In order to determine if these observed changes are from sea level rise or storm damage a monitoring program will need to be developed.

Sea Surface Temperature Change

Eleven of the years spanning 1995 to 2006 are ranked among the warmest 12 years of recorded global surface temperature (IPCC, 2007). Temperature change is another component that may impact the Monument's marine ecosystems. The NWHI are monitored as part of the Coral Reef Early Warning System (CREWS). The system provides managers and researchers with telemetered meteorological and oceanographic data at precise locations. In the NWHI, NOAA's PIFSC, Coral Reef Ecosystem Division (CRED) has deployed long-term moored observing stations, satellite-tracked drifting buoys, and subsurface instrumented moorings (Table 10.4 and Figure 10.7) Changes in SSTs will result in changes to available habitat for temperature dependent species and coral bleaching.

As SSTs change species currently using habitat near the surface may move to lower depths or different latitudes to find the appropriate habitat conditions. This will end up impacting other species dependent on these species. For example, seabirds feed on fish and other marine species near the ocean surface. As SST increases, seabird prey species move to deeper, cooler water, decreasing food availability for foraging birds, or requiring birds to fly further north in the Pacific to obtain food resources.

Changes in SST poses a threat to coral reef ecosystems in the form of coral bleaching. Corals are symbiotic organisms which secrete a hard, mineral calcium carbonate structure. The symbiosis is between microscopic, photosynthetic organisms called zooxanthellae that inhabit the soft tissue of the coral polyp. Zooxanthellae provide the pigmentation of the coral and produce energy which is donated to the host and contributes sig-

Table 10.4. Distribution of long-term oceanography monitoring buoys in the Monument.

LOCATION	CREWS-ENH[1]	CREWS-STD[2]	SST-ARGOS[3]	ODP[4]	WTR[5]	STR[6]
Kure	--	X	X	--	X	X
Midway	--	--	X	X	--	X
Pearl and Hermes	--	X	--	X	X	--
Lisianski	--	--	X	--	X	X
Laysan	--	--	X	--	--	X
Maro Reef	--	X	--	--	--	X
Gardner Pinnacles	--	--	--	--	--	X
French Frigate Shoals	--	--	--	--	--	X
Mokumanamana	--	--	--	--	--	--
Nihoa	--	--	--	--	--	--

[1] Coral Reef Early Warning System Enhanced - Moored buoys which provide high resolution SST, barometric pressure, wind speed, wind direction, and additionally provide salinity, UV-B, and PAR.
[2] Coral Reef Early Warning System Standard - Moored buoys which provide high resolution SST, barometric pressure, wind speed and wind direction. Subsets of these data are transmitted daily via satellite telemetry.
[3] Moored buoys which provide high resolution SST. Subsets of these data are transmitted daily via satellite telemetry.
[4] Subsurface Ocean Data Platform - Subsurface moorings, providing high resolution current profiles, directional wave spectra, and temperature and salinity.
[5] Subsurface moorings providing high resolution wave and tide records, temperature and conductivity.
[6] Subsurface moorings providing high resolution temperature. Additionally used on towed platforms for temperature and pressure-based depth.

nificantly to the ability of a coral to grow and reproduce. When a coral is stressed by higher than normal temperatures, sometimes as little as a 2-3°C increase in temperature above their optimal temperature, they expel their zooxanthellae into the water column resulting in a loss of color (Hoegh-Guldberg, 1999). In this bleached, energy depleted state a coral is more susceptible to disease infiltration and overgrowth by fast-growing turf algae. Anthropogenic activities resulting in increased nutrient loads, sedimentation and physical damage at the site can make bleaching events worse.

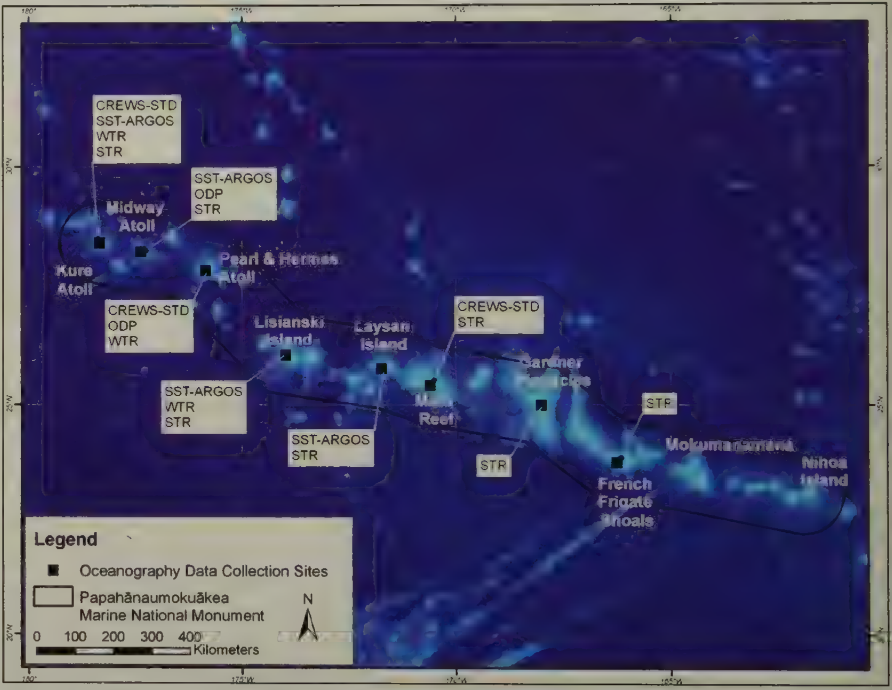


Figure 10.7. Locations of oceanography monitoring buoys in the NWHI. Map: K. Keller.

SST anomalies resulting from regional and global-scale climatic phenomena are believed to be the cause of bleaching in the NWHI. Mass coral bleaching in the NWHI occurred during late summer 2002 (Aeby et al., 2003; Kenyon and Brainard, 2006). This was the first ever recorded bleaching event known to occur in the NWHI. Coral bleaching occurred again at high levels in 2004, and was detected again at low rates in 2006 (Kenyon and Brainard, 2006). The corals in the NWHI were believed to be less susceptible to bleaching due to the high latitude location. Bleaching was most severe, however at the three northernmost atolls (Pearl and Hermes Atoll, Midway Atoll and Kure Atoll), which experience both higher and lower SSTs than other reefs of the NWHI. During the bleaching event, greater magnitude and longer durations of temperature anomalies were recorded and attributed to the bleaching events of 2002 (Hoeke et al., 2006). Lisisanski, Laysan and Maro experienced shorter and less severe temperature anomalies, resulting in comparatively minor bleaching events. Field investigations conducted in 2004 indicate that bleaching occurrence was highest in shallow back reef and patch reef habitats (Kenyon and Brainard, 2006). Researchers from the University of California, Santa Cruz are currently modeling circulation patterns at Midway Atoll to determine if anthropogenic changes to the flow and circulation patters may exacerbate bleaching events.

In addition to using field measurements it is possible to detect potential coral bleaching events using satellite information. NOAA's Coral Reef Watch produces near-real-time alerts from 24 selected reefs around the globe. Midway Atoll is one of the sites that is monitored. Figure 10.8 contains graphs indicating when Midway Atoll SSTs reached levels that are associated with beaching events. The graphs show the 2002 and 2005 SST associated with bleaching events were detected by NOAA's Coral Reef Watch prior to being documented in the field.

The development of a bleaching response plan is critical to effective reef management. This ensures that when a bleaching event occurs, decisive action can be taken as soon as possible to mitigate the effects of the bleaching event. The NWHI will require a unique response plan given that the region is largely free from local sources of anthropogenic stressors, so bleaching is largely a result of increased SSTs. However, managers will work to identify resilient areas based upon the best available information from monitoring data, research projects, past bleaching events and modelling. A bleaching response plan would call for identification of specific groups and actions that should take place prior to a bleaching event, during the event and follow up after SSTs have returned to normal.

Ocean Acidification

Coral reef systems maintain a delicate balance between calcification and erosional forces. For the reef to grow and accrete mass, the corals' ability to calcify must outrun the pressures put upon the system, such as bioerosion, physical erosion from wave action and storms and anthropogenic damage. The NWHI are relatively shielded from most anthropogenic effects due to their remoteness, but they are still subject to natural forces. The shallow and deep water coral reefs in the NWHI will potentially be impacted by changes in the carbonate levels in the ocean. If the reef

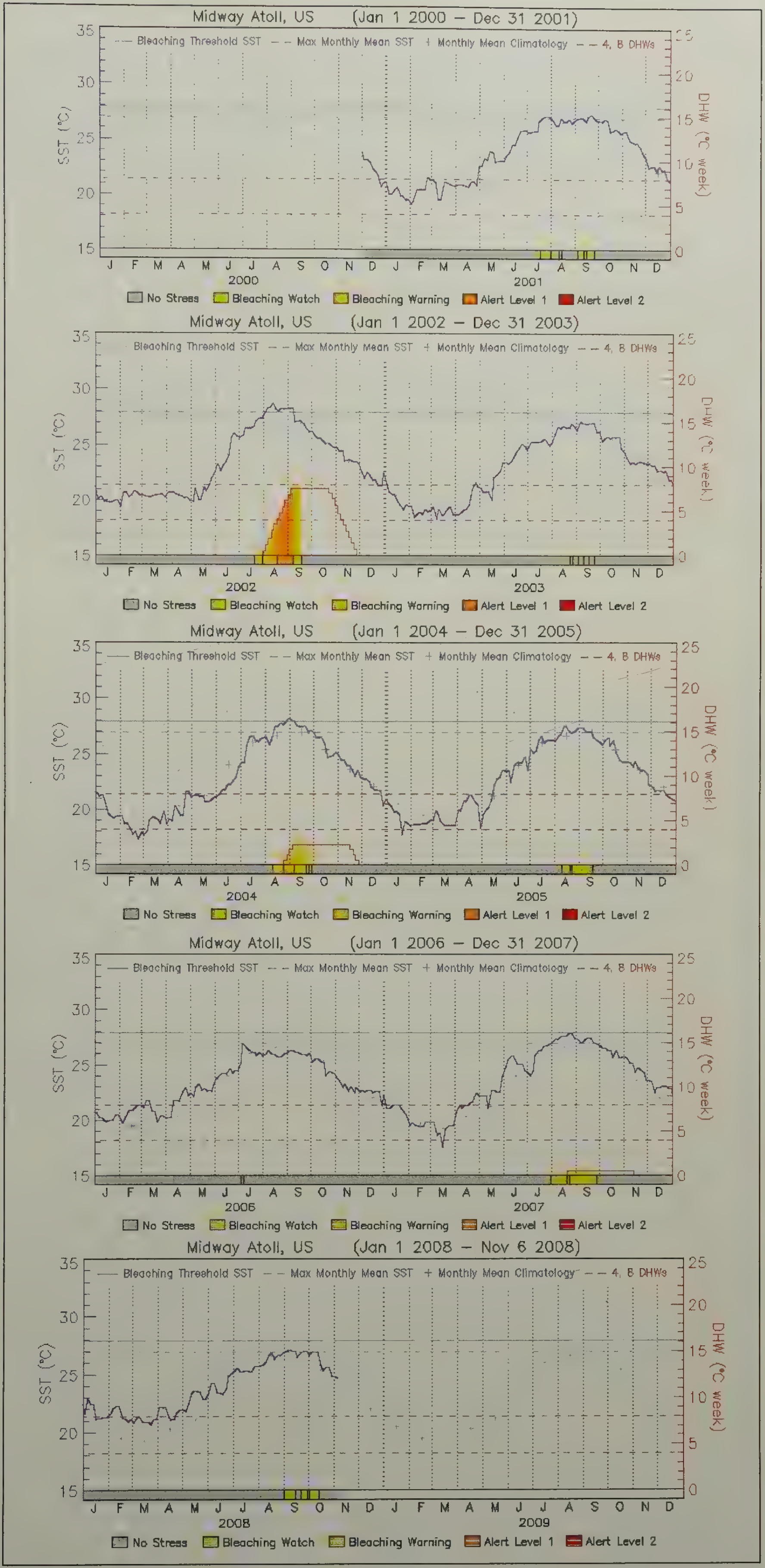


Figure 10.8. Sea surface temperature values recorded at Midway Atoll documenting potential conditions for coral bleaching events (2000 - 2008). Source: NOAA Coral Reef Watch.

structure changes there can be will be an ecosystem wide effect as habitat availability and species ranges change.

Evidence of undersaturation has been reported in the Intermediate Pacific in relatively shallow waters of between 200 m and 1,000 m (Feely et al., 2002). This is of concern to the NWHI deepwater habitat which for these purposes will be defined as depths greater than 50 m. A number of corals have identified habitat ranging from 20-3,000 m (Hourigan et al., 2008). These corals provide structure to the benthos as well as serving as habitat for other organisms living in the deep that have yet to be fully explored. Endangered Hawaiian monk seals with attached animal borne imaging systems (Crittercams) have been recorded foraging for fish that find shelter in black coral beds (Parrish and Baco, 2008). However, due to the remoteness of the NWHI follow-up deepwater surveys have yet to be conducted, as they require extensive time, planning and budgeting considerations. Deepwater corals are mainly slow-growing species, and the effects of undersaturation may not manifest for years after it has occurred. Or, conversely, if the saturation horizon rises to shallow depths, the aragonite structure of the deepwater corals may begin to dissolve away into the ocean.

The degree to which ocean acidification will affect Monument coral reefs is presently under investigation. Plans are underway to establish a baseline of the carbonate chemistry of the NWHI. This would be done by utilizing the CTD (conductivity, temperature, depth) sensor scanner onboard R/V *Hiialakai* and outfitting it with a pH sensor. Carbonate chemistry of a water sample can be characterized by taking three measurements; the dissolved inorganic carbon, alkalinity and pH. All three of these measurements are planned to be performed onboard during regular CTD casts and the seawater samples brought back for further analysis. These types of measurements, taken from deepwater habitats and lagoon waters (from small boat platforms) will help the Monument to develop an understanding of the current carbonate chemistry of the waters and allow us to monitor future changes.

Ocean Acidification

Ocean acidification is the process of seawater becoming less basic and is likely to upset the delicate balance between reef calcification and erosion (Hoegh-Guldberg, 1999). The carbonate equilibrium describes the process of calcification in marine animals and is illustrated by equation 1 (Kleypas et al., 1999; Royal Society, 2005; Kleypas and Langdon, 2006). Acidification, where atmospheric CO_2 is absorbed by the surface of the ocean where it forms carbonic acid, is illustrated by equation 2;. This acid then dissociates into free hydrogen and bicarbonate ions resulting in increasing amounts of bicarbonate, leaving less carbonate ions available to interact with the abundant calcium ions present in seawater. Calcium ions are not thought to be a limiting factor in calcification (Royal Society, 2005). Therefore, when the amount of CO_2 in the atmosphere increases, the availability of carbonate ions for calcifying organisms (corals, calcareous algae, plankton etc.) to incorporate into their skeletons decreases and the carbonate equilibrium shifts facilitating the dissolution of the calcium carbonate skeleton (Kleypas et al., 1999; Royal Society, 2005; Kleypas et al., 2006).

Equation 1: The Carbonate Equilibrium

$$\overset{\leftarrow \text{ Skeletal formation}}{\underset{\text{Skeletal dissolution} \rightarrow}{CaCO_3 + CO_2 + H_2O \leftrightarrows Ca^{2+} + 2HCO_3^-}}$$

Equation 2: Acidification

$$CO_2 + H_2O \leftrightarrows H_2CO_3 \leftrightarrows H^+ + HCO_3^- \leftrightarrows H^+ + CO_3^{2-}$$

There are two forms of calcium carbonate found in skeletons of $CaCO_3$ secreting organisms. The first is calcite, which is the less soluble form found in crustose coraline algaes, and the other is the aragonite form of calcium carbonate, which is utilized by scleractinian corals and other pteropods. There is a critical concentration of carbonate ions in seawater below which calcium carbonate will dissolve. The solubility of calcium carbonate is a function of depth and pressure. The critical concentration occurs at a depth known as the "saturation horizon", under which calcium carbonate structures tend to dissolve. Due to increased amounts of CO_2 in seawater and the resultant decrease in the carbonate ion concentration (equation 2) the saturation horizon will move ever shallower with increasing releases of anthropogenic CO_2 into the atmosphere. This means that the depth at which corals are able to calcify will grow shallower as more CO_2 is input into the atmosphere. Latitude also plays a role when looking at where saturation boundaries occur. Lower latitudes near the equator tend to have saturation states conducive to the solidified structure of corals, while poleward areas are already showing evidence of undersaturation at the surface waters. Currently the surface waters of the NWHI still fall within saturation parameters (Feely et al., 2002).

Marine Debris

A multiagency effort initially launched in 1996 by the University of Hawaii's Sea Grant College Program began to address the problem of marine debris, a problem that was much larger than any one agency alone can resolve. An estimated 750 to 1,000 tons of marine debris were on reefs and beaches in the NWHI (NOAA PIFSC, unpublished; Figure 10.9). NOAA, in collaboration with 14 other partners including the U.S. Coast Guard (USCG), Schnitzer Steel Hawaii Corporation (formerly Hawaii Metals Recycling Company), the Hawaii Sea Grant College Program, U.S. Navy, USFWS, the City and County of Honolulu, the state of Hawaii, The Ocean Conservancy, Hawaii Wildlife Fund, Matson Navigation Company, and others removed 66 tons of marine debris and derelict fishing gear from 1996 to 2000. In 2001, the multiagency cleanup effort was extended, resulting in a corresponding increase of marine debris removed from reefs and beaches of the NWHI (Table 10.5). The total amount of marine debris removed from 1996 to 2007 was 582 tons.

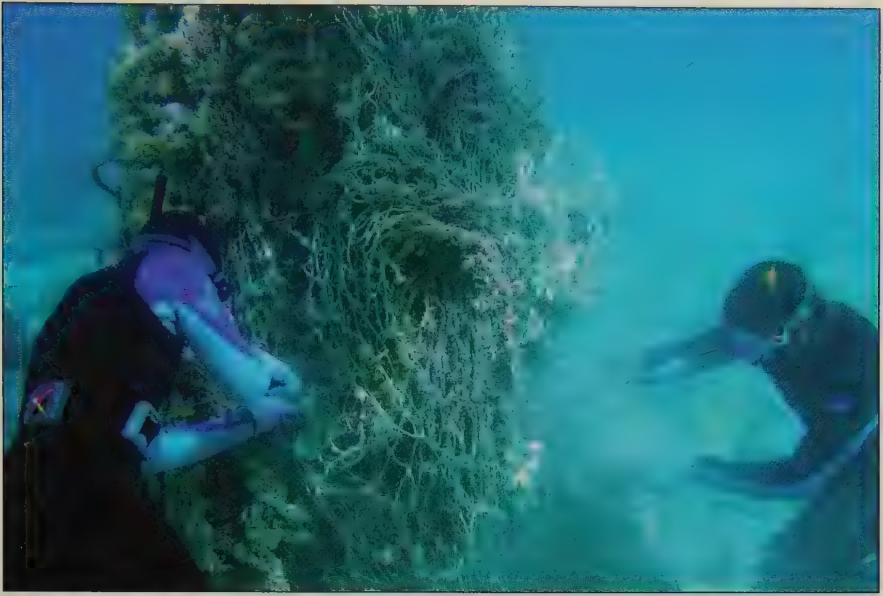


Figure 10.9. Divers cutting away nets from the reef in the NWHI. Photo: CRED.

Table 10.5. The total amount of marine debris removed from 1996 to 2007 was 582 tons. Source: NOAA/PIFSC.

YEAR	TONS REMOVED
1996 - 2000	Approximately 25 tons per year
2001	68
2002	107
2003	118
2004	126
2005	57
2006	21
2007	59

The source of much of the marine debris is fishing nets discarded or lost in the northeastern Pacific, well outside of the Monument boundaries. In order to address the source of marine debris in the Pacific, Monument managers will need to work with international partners to look at methods and develop policies for reducing marine debris. Even if all new input of debris were stopped, existing debris in the ocean would continue to accumulate in the NWHI for years to come. At a Pacific basin scale, it is suggested that the subtropic convergence zone (STCZ) that moves between 25°N and 35°N is an area of high ghostnet retention (Figure 10.10). When the STCZ moves within range of the NWHI, the nets often become entangled on reefs and continue to be an entanglement hazard for many species. Once the debris reaches the NWHI, the rate of accumulation of nets on reefs varies by island and atoll and within island and atoll

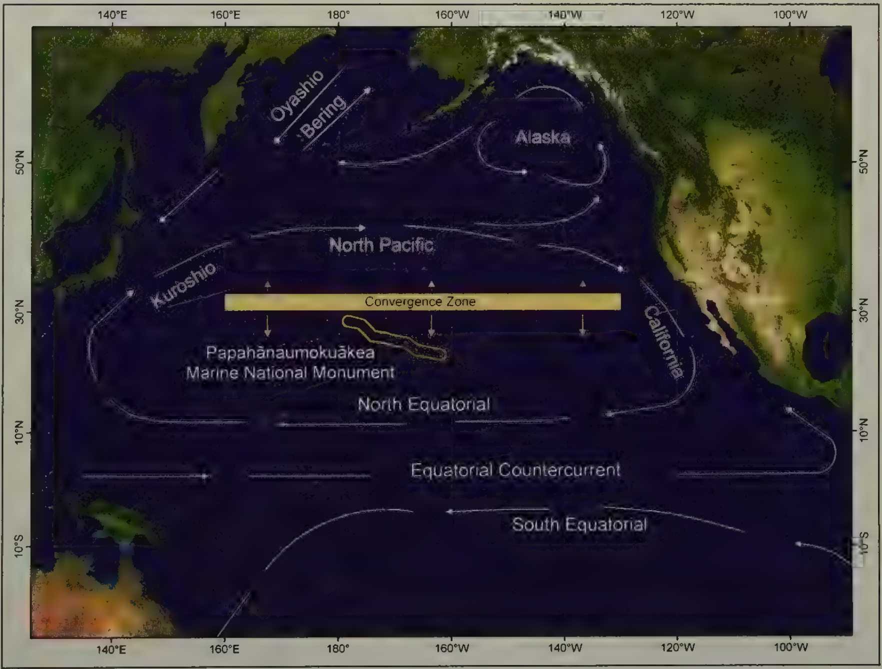


Figure 10.10. Map illustrating regional current movements and the convergence zone.

(Dameron et al., 2007). A model of potential accumulation rates was developed for the NWHI to help evaluate the distribution of marine debris and where efforts should be focused for removal. The results from the model can be used by managers to target areas for marine debris clean-up efforts.

In the 2007 field season Kure Atoll, Pearl and Hermes Atoll, Lisianski Island, Laysan Island and French Frigate Shoals were targeted for marine debris removal (Table 10.6). In addition to the marine debris removal efforts, a study of the effects of marine debris and marine debris removal on NWHI coral reef benthic communities was initiated at Midway Atoll in 2008. The study will be assessing the long-term effects of removal of nets from reefs as well as the effects of nets left in place. Initial survey and removal efforts began in August 2008 and the study will continue into 2009. The results of the study will help managers develop better guidelines for marine debris removal and decreasing overall impact to the coral reef ecosystems. In addition the results will begin to provide managers with information about recovery rates of the benthic communities following debris removal or other anthropogenic disturbance.

Table 10.6. 2007 field season marine debris removal by island and atoll. Source:

LOCATION	DEBRIS TYPE	REMOVED (kg)	REMOVED (tons)
French Frigate Shoals	Marine Debris	5,554	6
	Land Debris	1,735	2
Kure	Marine Debris	2,860	3
	Land Debris	1,431	1
Laysan	Marine Debris	0	0
	Land Debris	2,073	2
Lisianski	Marine Debris	0	0
	Land Debris	4,396	4
Pearl and Hermes	Marine Debris	39,250	39
	Land Debris	1,911	2
Total Marine Debris Weight		**47,664**	**48**
Total Land Debris Weight		**11,546**	**12**
Total Debris Weight		**59,210**	**59**

Marine Alien Species

Monument managers have identified marine invasive species including pathogens as a significant threat and are taking action to prevent any additional introductions. Because of the Monument's vast size, it is difficult to carry out surveys to detect marine invasive species. However, based on the few surveys conducted (see Nonindigenous and Invasive Species Chapter), there are currently 13 marine invasive species that have been identified and documented in the NWHI. Compared to the 343 marine invasive species that have been identified and documented in the Main Hawaiian Islands (MHI), the NWHI have a relatively low abundance of invasive species (Eldredge and Carlton, 2002; Godwin et al., 2006; Godwin, 2008). The potential of additional introductions of non-indigenous species in the NWHI could have dramatic consequences to the ecosystem. Management tools to reduce the potential introduction and spread of alien species in the Monument are the permitting process, enforcement of regulations and development of a monitoring and research program.

Mandatory hull inspections for all permitted vessels are the primary tool managers can use to reduce the potential of marine alien species introductions. Prior to receiving a Monument permit, any ship that has applied for a permit to access the Monument must complete a hull inspection. Another mechanism for potential introductions is by way of ballast water exchange. In response to national concern regarding invasive species, the National Invasive Species Act of 1996 was enacted. The Act reauthorized and amended the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990. In addition to the Monument discharge regulations, ballast water exchange in the Monument is regulated by the USCG which codified a national mandatory ballast water management program for all vessels equipped with ballast water tanks that enter or operate within U.S. waters. These regulations also require vessels to maintain a ballast water management plan that is specific for that vessel and that assigns responsibility to the master or an appropriate official to understand and execute the ballast water management strategy for that vessel.

There have been several reports written recently on the topic of marine invasive species in the NWHI (Eldredge, 2005; Godwin et al., 2006; and Godwin, 2008). They provide a number of recommendations for managers to deal with invasive species. These reports provided the foundation for the prohibitions on ballast discharge in the Proclamation and the actions outlined in the MMP Alien Species Action Plan. The Alien Species Action Plan addresses prevention, monitoring of alien species, and education of Monument users and the public about the need to prevent alien species introductions. The following section focuses on how managers can utilize the geographic locations of known marine invasive species to shape their actions in three distinct realms: monitoring, permitting and research.

Monitoring

The locations of existing alien species populations can provide a foundation for future monitoring efforts. Monitoring of existing infestations and identification of new infestations is a key component to the Alien Species Action plan in the MMP. In the past, relatively few marine invasive surveys were conducted and usually only once and often opportunistically. The MMP calls for the need to establish a coordinated and systematic effort to survey distributions and populations of known alien species at regular intervals. Understanding where existing populations are can help guide managers in the development of monitoring protocols for the detection and potential eradication of current populations as well as future infestations. The monitoring program will provide important information on the spatial distribution, spread and population sizes of marine alien species within the Monument. Currently the existing Rapid Assessment and Monitoring Program monitoring does not specifically target alien species, but alien species would be identified during the MMP proposed alien species monitoring surveys.

Permitting

Knowing the locations of marine invasive species can assist managers in making decisions regarding the issuance of permits in the Monument. An understanding of potential invasive vectors, combined with the knowledge of where marine invasive species reside in the MHI and NWHI will allow managers to take steps to minimize those vectors. Steps to minimize the introduction of potential invasive vectors can most effectively be implemented through the permitting process.

Activities authorized under a Monument permit can be structured so that vessels visit the islands in an order that minimizes the risk of transporting invasive species. The more pristine sites should be visited first, and the most invaded locations last, to minimize the likelihood of organisms being transported from invaded sites to pristine areas. This may not always be possible but can be implemented where possible. These recommendations are currently being done on an informal basis through consultations with the applicant, but they could be formally incorporated as permit conditions in the final permit.

Managers can also restrict where vessels anchor or identify a route through the NWHI so as to minimize the risk of spreading invasive species through hull fouling or ballast water. To make effective decisions that can be justified, managers must have good geographic information on the locations of marine invasive species within the Monument.

Research

Information about where marine invasive species reside in the Monument is needed to inform managers and can serve as a guide on how best to direct management-driven research. Research about the effects of invasive species can be effectively targeted to the locations where known populations of those species do or do not exist. Accurate information about the abundance and positions of invasive species can help prioritize research based on species or sites. Research should be directed at the more abundant species, or the species in more vulnerable sites. In addition, other research that should be undertaken includes factors that cause alien species to become invasive and the interactions between native and alien species.

Vessel Hazards

With the exception of a few small boats at Midway Atoll, French Frigate Shoals, Pearl and Hermes and Kure Atoll, no vessels have home ports in the NWHI. Therefore, almost all marine traffic in the waters surrounding the NWHI is the result of transiting merchant vessels, research ships, fishing vessels, cruise ships, USCG ships and recreational vessels which visit infrequently. An estimated 50 vessels pass through the U.S. EEZ surrounding the NWHI each day (Franklin, 2008). Vessels entering shallow waters intentionally or unintentionally have a higher risk of impacting resources.

Hazards to shipping and other forms of maritime traffic such as shallow submerged reefs and shoals are inherent in the NWHI's 1,931 km of islands and atolls. The region is exposed to open ocean weather and sea conditions year-round, punctuated by winter severe storm and wave events. Vessel groundings and the release of fuel, cargo and other items pose real threats to the NWHI. A number of factors have contributed to vessel groundings and cargo loss over the years. These factors include human error, lack of appropriate navigational practices, inaccurate nautical charts, and treacherous conditions due to low-lying islands, atolls, and shallow pinnacles and banks. Periodically, accidental loss of cargo overboard causes marine debris or hazardous materials to enter sensitive shallow-water ecosystems.

The history of shipwrecks and groundings is as old as the history of ships in the NWHI. Many islands and atolls are named for ships that went aground. In the last 50 years this history has continued, with several vessel groundings (Figure 10.11). Most recently the *Paradise Queen* and *Grendel* went aground at Kure Atoll in 1998 and 2007, respectively, and the *Swordman II* and *Casitas* went aground at Pearl and Hermes Atoll in 2000 and 2005, respectively.

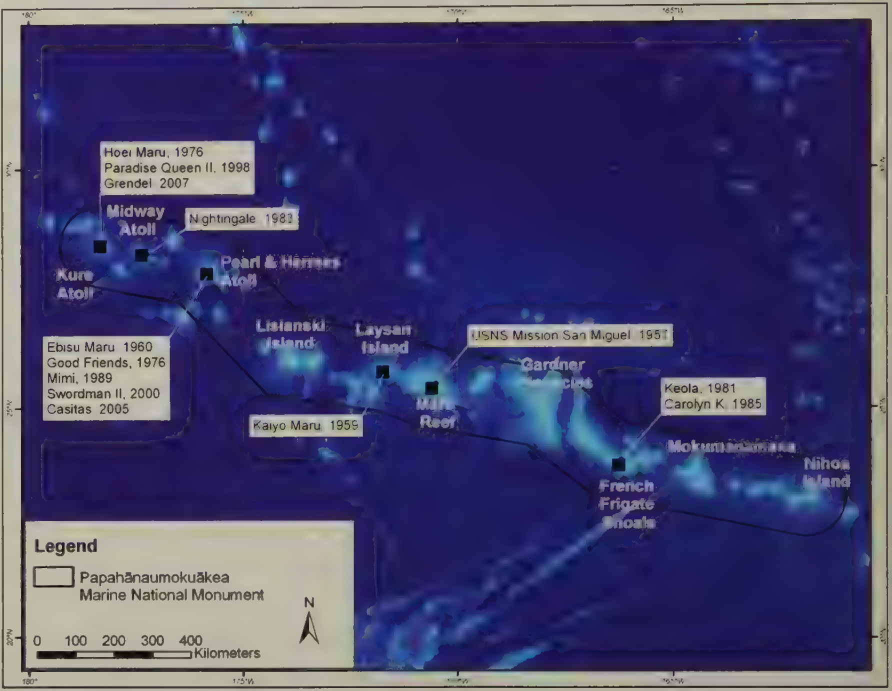


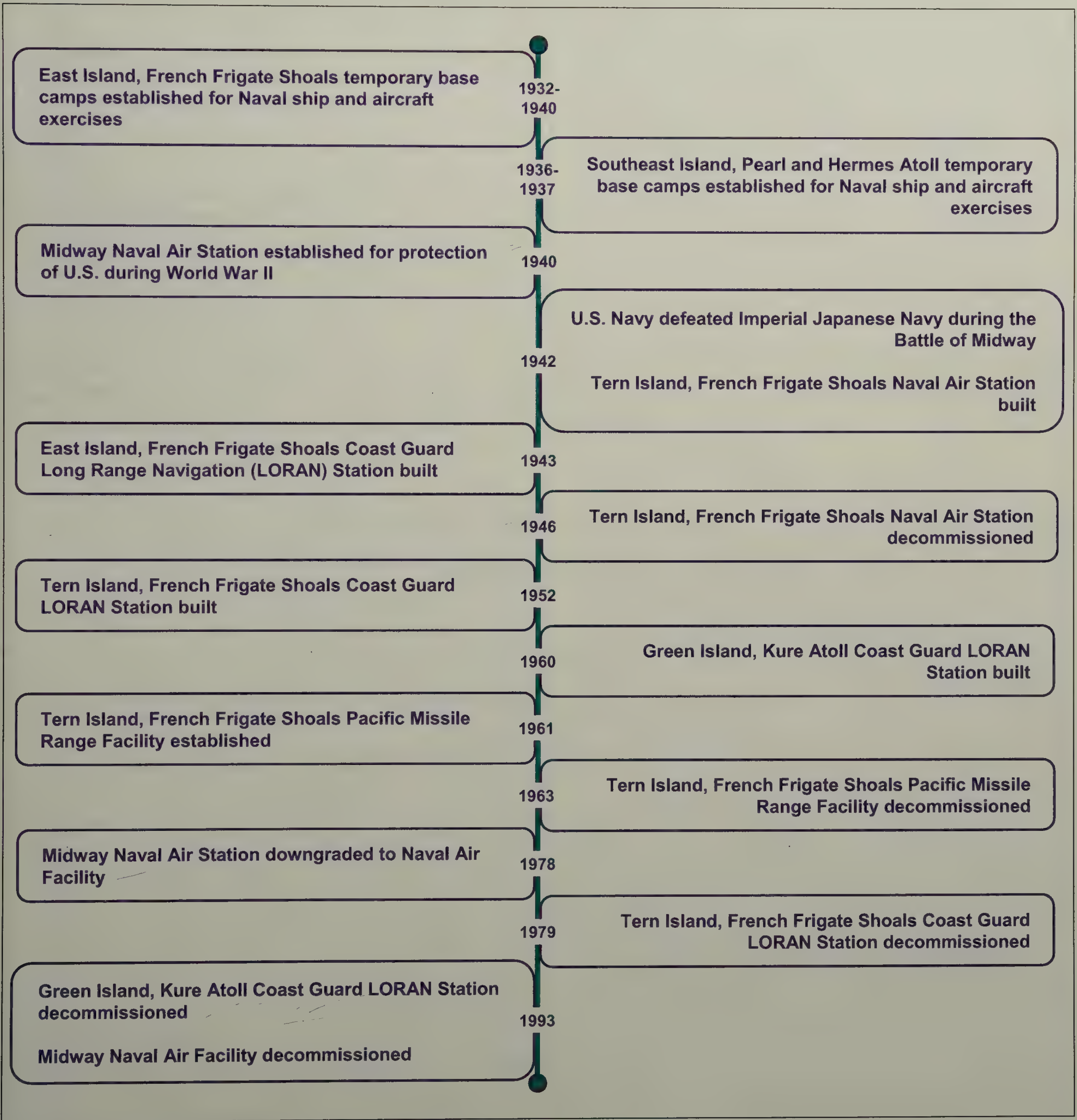
Figure 10.11. Groundings in the NWHI in the last 60 years. Map: K. Keller.

Unexploded ordnance, debris and modern shipwrecks, such as the fishing vessels *Houei Maru #5*, the *Paradise Queen II* at Kure Atoll or the tanker *Mission San Miguel* lost at Maro Reef, are not protected as maritime heritage resources and represent a more immediate concern as threats to reef ecosystems. Mechanical damage from the initial grounding, subsequent redeposition of wreck material by storm surge, fishing gear damage to reef and reef-associated organisms, and release of fuel or hazardous substances are all issues to be considered in protecting the integrity of the environment. Dissolved iron serves as a limiting nutrient in many tropical marine areas and tends to fuel cyanobacteria (blue-green algae) or other iron limited species growth when the iron begins to dissolve and corrode. This is a problem particularly on atolls and low coral islands where basaltic or volcanic rock is absent in the photic zone and natural sources of dissolved iron in seawater are minimal. Therefore, any ships left in place would be an iron source that could contribute to potential cyanobacterial blooms. It has been demonstrated that not removing nonhistoric steel vessels will have long-term detrimental effects, which in most cases can be worse than any short-term damage to the environment caused by the removal action. Vessel traffic can also affect natural resources through direct damage to the reef from anchors, waste discharge, light and noise. Monument regulations which prohibit anchoring on or having a vessel anchored on any living or dead coral to prevent anchor damage to reefs. Discharge of waste in the Monument is also regulated by Proclamation and permit requirements.

The designation of the PSSA and expansion of the ATBA is intended to reduce the potential for large vessel groundings within the Monument. In near shore areas, the mandatory requirement for a vessel monitoring system will allow better tracking of permitted vessels as well as provide information for emergency response thus reducing any potential impact from vessel grounding. Reducing the response time when groundings do occur will also minimize environmental impacts.

MANAGEMENT OF HUMAN IMPACTS

There is a long history of managing impacts from human activities in the NWHI. Beginning in the early 1900s, several federal and state agencies, including the Department of Defense, Department of Agriculture, Department of the Interior, the state of Hawaii, and the Department of Commerce were assigned protective responsibilities in the NWHI. Additionally, military defense needs during and after World War II required the construction of facilities and the presence of U.S. Navy and U.S. Air Force, and USCG stations on several islands in the northwestern archipelago through the end of the 20th century. The following figures (Figures 10.12 and 10.13) indicate periods of protective responsibilities of the various federal and state agencies and the time periods in which military presence occurred in the NWHI. The following section focuses on the management of human activities since the designation of the Monument.



1932-1940 — **East Island, French Frigate Shoals temporary base camps established for Naval ship and aircraft exercises**

1936-1937 — **Southeast Island, Pearl and Hermes Atoll temporary base camps established for Naval ship and aircraft exercises**

1940 — **Midway Naval Air Station established for protection of U.S. during World War II**

1942 — **U.S. Navy defeated Imperial Japanese Navy during the Battle of Midway**

Tern Island, French Frigate Shoals Naval Air Station built

1943 — **East Island, French Frigate Shoals Coast Guard Long Range Navigation (LORAN) Station built**

1946 — **Tern Island, French Frigate Shoals Naval Air Station decommissioned**

1952 — **Tern Island, French Frigate Shoals Coast Guard LORAN Station built**

1960 — **Green Island, Kure Atoll Coast Guard LORAN Station built**

1961 — **Tern Island, French Frigate Shoals Pacific Missile Range Facility established**

1963 — **Tern Island, French Frigate Shoals Pacific Missile Range Facility decommissioned**

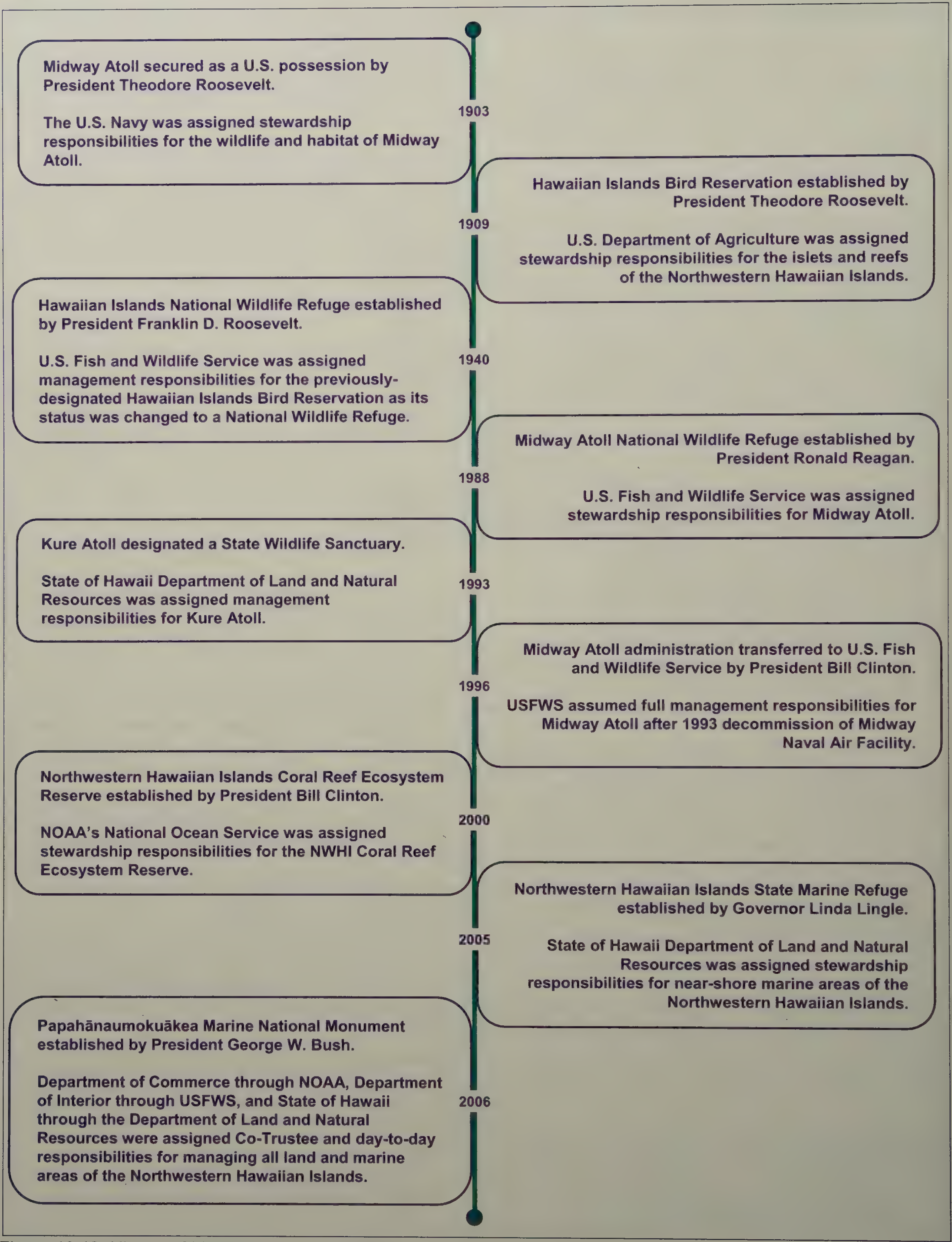
1978 — **Midway Naval Air Station downgraded to Naval Air Facility**

1979 — **Tern Island, French Frigate Shoals Coast Guard LORAN Station decommissioned**

1993 — **Green Island, Kure Atoll Coast Guard LORAN Station decommissioned**

Midway Naval Air Facility decommissioned

Figure 10.12. History of military presence in the NWHI.



1903

Midway Atoll secured as a U.S. possession by President Theodore Roosevelt.

The U.S. Navy was assigned stewardship responsibilities for the wildlife and habitat of Midway Atoll.

1909

Hawaiian Islands Bird Reservation established by President Theodore Roosevelt.

U.S. Department of Agriculture was assigned stewardship responsibilities for the islets and reefs of the Northwestern Hawaiian Islands.

1940

Hawaiian Islands National Wildlife Refuge established by President Franklin D. Roosevelt.

U.S. Fish and Wildlife Service was assigned management responsibilities for the previously-designated Hawaiian Islands Bird Reservation as its status was changed to a National Wildlife Refuge.

1988

Midway Atoll National Wildlife Refuge established by President Ronald Reagan.

U.S. Fish and Wildlife Service was assigned stewardship responsibilities for Midway Atoll.

1993

Kure Atoll designated a State Wildlife Sanctuary.

State of Hawaii Department of Land and Natural Resources was assigned management responsibilities for Kure Atoll.

1996

Midway Atoll administration transferred to U.S. Fish and Wildlife Service by President Bill Clinton.

USFWS assumed full management responsibilities for Midway Atoll after 1993 decommission of Midway Naval Air Facility.

2000

Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve established by President Bill Clinton.

NOAA's National Ocean Service was assigned stewardship responsibilities for the NWHI Coral Reef Ecosystem Reserve.

2005

Northwestern Hawaiian Islands State Marine Refuge established by Governor Linda Lingle.

State of Hawaii Department of Land and Natural Resources was assigned stewardship responsibilities for near-shore marine areas of the Northwestern Hawaiian Islands.

2006

Papahānaumokuākea Marine National Monument established by President George W. Bush.

Department of Commerce through NOAA, Department of Interior through USFWS, and State of Hawaii through the Department of Land and Natural Resources were assigned Co-Trustee and day-to-day responsibilities for managing all land and marine areas of the Northwestern Hawaiian Islands.

Figure 10.13. History of Management in the NWHI.

MONUMENT PERMIT APPLICATIONS AND PERMIT ISSUANCE

Since the designation of the Monument, all activities conducted within the Monument boundaries must meet the findings of the Proclamation and obtain a permit from the Monument. The Monument permitting program is one of the management tools that the Co-Trustees use to regulate the potential impacts of human activities on the Monument resources. Prior to the establishment of the Monument, the separate agencies responsible for management of the NWHI had separate permit applications, reviews and issuance processes and their own permit reporting requirements. Under Co-Trustee management, activities in the NWHI are prohibited, with limited exception, unless authorized by a Monument permit. Applications for all applicable activities are reviewed and permits issued jointly by the three Co-Trustee agencies.

A joint Monument permit application template and review process were developed and implemented in 2007. All applications are reviewed by managers, scientists, other experts within the three Monument Co-Trustee agencies and by Native Hawaiian cultural reviewers. In addition, summaries of permit applications are posted for public notification, and all applications for activities in State waters must be posted in full for public review before they are considered for approval by the State of Hawaii Board of Land and Natural Resources Land Board.

In order for a project to be permitted, it must comply with National Environmental Policy Act requirements and all other federal and state required permits and consultations. In addition, any permitted activity must meet all of the Findings of the Presidential Proclamation (Proclamation 8031) establishing the Monument. Information on Monument permit application procedures is available at http://papahanaumokuakea.gov/resource/permits.html.

In addition to meeting the findings in the Proclamation, proposed activities to be conducted in the Midway Atoll SMA and the other National Wildlife Refuge areas, proposed activities continue to be subject to findings of appropriateness (603 FW 1) and compatibility determinations (16 U.S.C. 668dd-668ee and 603 FW 2) by USFWS to ensure the activities meet the purposes for establishing the Hawaiian Islands and Midway Atoll National Wildlife Refuges and the mission of the National Wildlife Refuge System.

Findings of Presidential Proclamation 8031

- ☐ The activity can be conducted with adequate safeguards for the resources and ecological integrity of the Monument.
- ☐ The activity will be conducted in a manner compatible with the management direction of the Proclamation, considering the extent to which the conduct of the activity may diminish or enhance Monument resources, qualities, and ecological integrity; any indirect, secondary, or cumulative effects of the activity; and the duration of such effects.
- ☐ There is no practicable alternative to conducting the activity within the Monument.
- ☐ The end value of the activity outweighs its adverse impacts on Monument resources, qualities, and ecological integrity.
- ☐ The duration of the activity is no longer than necessary to achieve its stated purpose.
- ☐ The applicant is qualified to conduct and complete the activity and mitigate any potential impacts resulting from its conduct.
- ☐ The applicant has adequate financial resources available to conduct and complete the proposed activity and mitigate any potential impacts resulting from its conduct.
- ☐ The methods and procedures proposed by the applicant are appropriate to achieve the proposed activity's goals in relation to their impacts to Monument resources, qualities, and ecological integrity.
- ☐ The applicant's vessel has been outfitted with a mobile transceiver unit approved by NOAA Office of Law Enforcement and complies with the requirements of Proclamation 8031.
- ☐ There are no other factors that would make the issuance of a permit for the activity inappropriate.

Types of Permits Issued

Applicants can apply for Monument permits under the following six permit categories: Research, Conservation and Management, Education, Native Hawaiian Practices, Recreation and Special Ocean Use.

Research

Research permits are authorized for those activities that enhance the understanding of Monument resources and improve resource management decision making. Priority is given to research proposals that help to meet the management needs of the Monument Co-Trustee agencies. Examples of types of activities issued under a research permit include biological inventories, ecosystem-based research, benthic mapping, habitat characterization, restoration investigations, cultural studies, and terrestrial and marine archaeological research.

Conservation and Management

Conservation and Management permits are authorized for those activities that are required for general management of the Monument. This may include activities associated with resource management, such as field station operations, marine debris removal, development and maintenance of infrastructure, species and habitat restoration, and long-term resource monitoring programs such as monitoring of endangered species, seabird populations, and terrestrial native plant communities. Conservation and Management permits also provide a mechanism enabling rapid response and follow-up to critical events in the Monument that cannot be anticipated, such as vessel groundings, coral bleaching episodes and invasive species detection.

Education

Education permits are authorized for those activities that further the educational value of the Monument. These activities may enhance the understanding of ecosystems, improve resource management decision making, promote Native Hawaiian knowledge and values, or aid in enforcement and compliance efforts. Priority is given to those activities that have clear educational or public outreach benefits and that promote "bringing the place to the people, rather than the people to the place." Examples of past projects issued under an education permit include teacher-at-sea programs, distance learning projects, and university classes.

Native Hawaiian Practices

Activities conducted under a Native Hawaiian Practice permit must be noncommercial, deemed appropriate and necessary by traditional standards, benefit the NWHI and Native Hawaiian community, perpetuate traditional knowledge and restrict the consumption of harvested resources from the Monument. Examples of activities permitted under a Native Hawaiian Practice permit include the entry of vessels for the purpose of applying and transferring knowledge of traditional navigation techniques and conducting ceremonies at historic cultural sites on Nihoa or Mokumanamana. Permit conditions and protocols for Native Hawaiian Practice permits will continue to be developed by the Monument Management Board, including the Office of Hawaiian Affairs through consultation with the Native Hawaiian Cultural Working Group and the Native Hawaiian community.

Recreation

Recreation permits are limited to the Midway Atoll Special Management Area in the Monument. Recreational activities may not be associated with any for-hire operation or involve any extractive use. Examples of recreational activities that may be permitted include snorkeling, SCUBA diving, wildlife viewing and kayaking.

Special Ocean Use

Special Ocean Use permits are authorized for those projects related to commercial ocean uses, such as ecotourism or documentary filmmaking, that have a demonstrated net benefit to the Monument. Special Ocean Use is defined as any activity or use of the Monument that will generate revenue or profits for one or more of the persons associated with the activity or use. Activities that could potentially qualify as another permit type but that directly generates revenue or profit for at least one of the persons involved in the activity can only be permitted as Special Ocean Use. In addition, Special Ocean Use proposals involving activities outside of the Midway Atoll Special Management Area must have demonstrated educational or research purposes that directly benefit the conservation and management of the Monument.

Emergencies, Law Enforcement Activities and Armed Forces Actions

Permits are not required for those activities conducted within the Monument that are necessary to respond to emergencies or that are necessary for law enforcement purposes. Activities and exercises of the Armed Forces (including those carried out by the USCG) do not require a permit but must be conducted consistent with applicable federal laws. All other human presence, including activities conducted by the Co-Trustee agencies, require review and approval through the Monument permitting process.

Transit Without Interruption Through the Monument

Uninterrupted passage by vessels through the Monument does not require a permit but vessel operators must provide official notice prior to entering and upon departing. Official notification ensures that managers know at any given time who is present in the Monument either conducting activities under an authorized permit or transiting without interruption

Additional Federal and State Permits and Consultations Required for Work in the Monument

In addition to the permit requirements of the Monument, several other federal and state permits and/or consultations are required for many of the activities conducted in the NWHI. For example, all personnel working with threatened or endangered species must obtain an endangered species permit. Anyone handling any bird species must obtain one or more permits from the U.S. Fish and Wildlife Service Office of Migratory Bird Management, and all scientists working with marine mammals must obtain one or more permits from the NOAA Fisheries Office of Protected Resources. Consultations may also be required as described under the U.S. ESA or Environmental Protection Agency regulations. Finally, although bottomfishing within the Monument boundaries will be phased out in 2011, all current bottomfishing operations are required to have valid federal fishing permits and state commercial marine licenses and fishing vessel registrations to operate within the Monument

2007 Permitted Activities Conducted Within the Monument

The first full year in which permits were issued by the Monument was 2007. Prior to June 2007, the State of Hawaii issued separate State permits for the Monument. Of a total of 51 permitted projects in the Monument in 2007, six were issued both Monument and state permits. The remaining 45 projects were issued a single joint Monument permit, issued by all three Co-Trustee agencies. Table 10.7 presents information on the number of permits issued, by permit type, for activities conducted in the Monument in 2007. The numbers of newly permitted projects and renewal projects (i.e., ongoing or long-term projects initiated in previous years) are shown.

Table 10.7. Numbers of Monument permits granted, by permit type, for activities conducted in 2007. Numbers of projects that were newly-initiated in 2007 and renewal projects (ongoing or long-term projects initiated in previous years) are also listed.

PERMIT TYPE	NUMBER OF MONUMENT PERMITS GRANTED	NUMBER OF NEW NWHI PROJECTS	NUMBER OF RENEWAL NWHI PROJECTS
Research	37	16	21
Conservation and Management	5	0	5
Education	2	2	0
Native Hawaiian Practices	1	1	0
Recreation	1	1	0
Special Ocean Use	5	5	0
TOTAL	**51**	**25**	**26**

Human activity in the NWHI has been greatly reduced relative to the height of military activity associated with World War II. Between 1940 -1945 more than 3,000 people were stationed at Midway Atoll and approximately 125 were stationed at Tern Island wintin French Frigate Shoals. (Amerson, 1971). The overall level of human presence in the Monument in 2007 is indicated in Table 10.8. Eighteen ship cruises and a total of 99 flights transported permitted personnel and supplies to and from the Monument. The average number of people aboard ship per day throughout the year was 32, and the average number of people on land per day throughout the Monument was 83, for a total average of 115 people in the Monument per day in 2007. The number of people on land per day was highest at Midway Atoll, with an average human population of 70. Human presence on all other islands and atolls was an order of magnitude lower, with an average of 6.3, 4.2, and 1.5 people on land per day at French Frigate Shoals, Laysan Island and Kure Atoll, respectively, and on average, less than one person per day on all other islands and atolls in the chain.

The following map (Figure 10.14) indicates locations where permitted activities occurred in the Monument in 2007. Many of the permits issued allowed for work to be conducted at multiple locations. Thus, for example, a single permit may have included work only at French Frigate Shoals, or it may have allowed for visits to all islands and atolls. In 2007 the majority of the activities occurred at Midway Atoll, Pearl and Hermes Atoll and French Frigate Shoals. Midway Atoll and French Frigate Shoals have relatively easy access and the infrastructure to support activities, including landing strips and facilities to house year-round personnel.

In order to assess cumulative impacts, it is important for managers to understand the trends and patterns of the different types of permitted activities that have occurred in the Monument. The following section spatially represents the distribution of activities that took place in the Monument by the types of permits issued in 2007

Table 10.8. Number of ship cruises and flights, and average number of people on land per day in the Monument in 2007.

TRANSPORTATION	
Number of Ship Cruises	18
Number of Flights	
French Frigate Shoals	13
Midway Atoll	86
VISITATION	
Average Number of People on Land per Day	83
Nihoa	0.02
Mokumanamana	0.06
French Frigate Shoals	6.30
Laysan	4.20
Lisianski	0.30
Pearl and Hermes Atoll	0.80
Midway Atoll	70.0
Kure Atoll	1.50
Average Number of People on Ships per Day	**32**
Average Number of People in Monument per Day	**115**

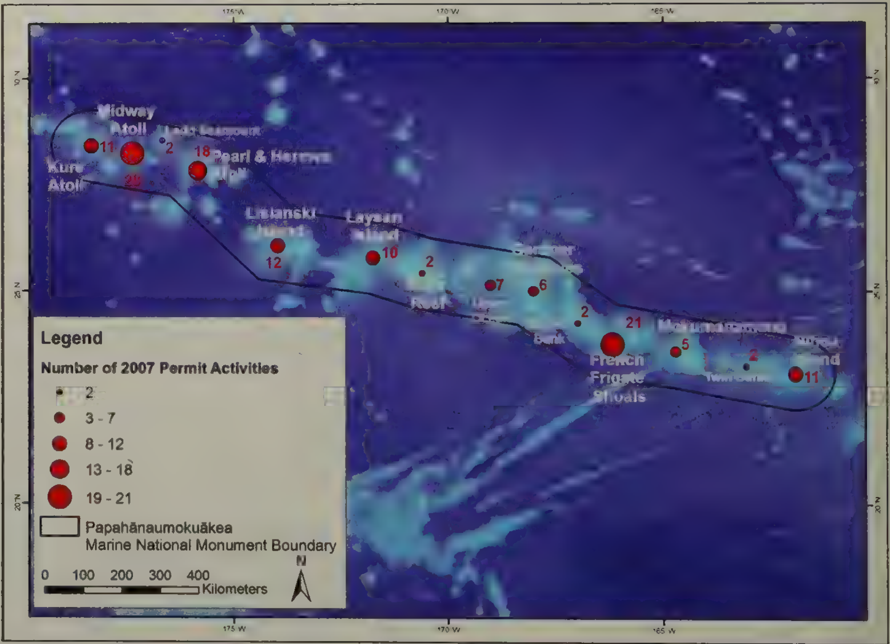


Figure 10.14. Locations of all permitted activities within the Monument in 2007. Map: K. Keller.

Research Activities by Location

Islands and atolls with the highest levels of permitted Research activities in 2007 included French Frigate Shoals, Pearl and Hermes Atoll, and Midway Atoll (Figure 10.15). Non-emergent banks and reefs, including Twin Banks, St. Rogatien and Brooks Banks, and Maro Reef, saw the lowest levels of research activities, while Mokumanamana and Gardner Pinnacles had the fewest number of Research activities conducted on emergent lands. Managers can use information on the distribution of past research activities to better plan and target future research and to ensure that data gaps are filled for those areas for which with less information is available.

Conservation and Management Activities by Location

In 2007, U.S. Fish and Wildlife Service Conservation and Management activities took place at Nihoa, French Frigate Shoals, Laysan, and Pearl and Hermes Atoll (within Hawaiian Islands National Wildlife Refuge), and at Midway Atoll (Midway Atoll National Wildlife Refuge). State of Hawaii DLNR activities took place at Kure Atoll, and NOAA PIFSC-CRED marine debris removal activities occurred at French Frigate Shoals, Laysan, Lisianski, Pearl and Hermes Atoll, and Kure Atoll (Figure 10.16).

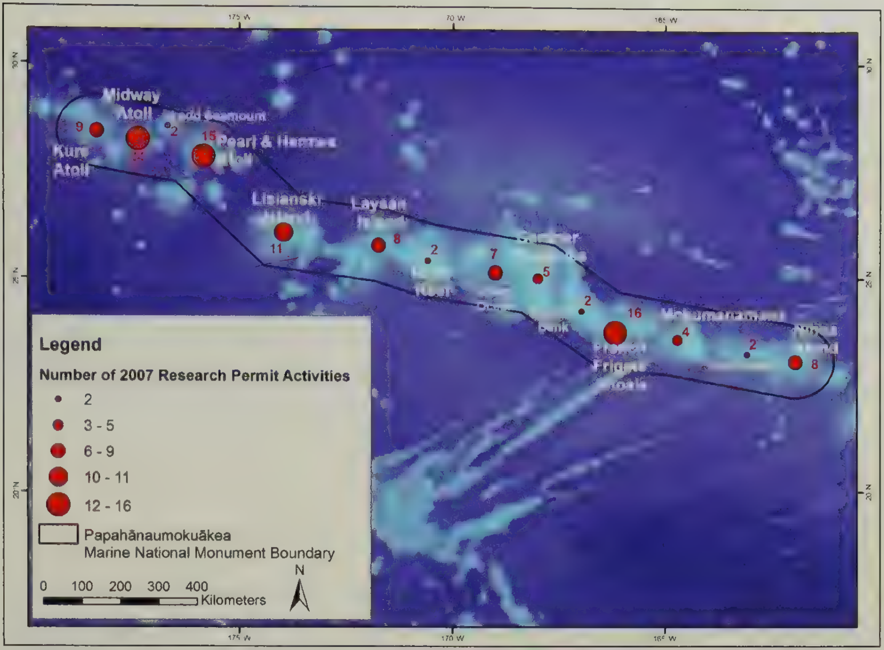


Figure 10.15. Locations of permitted Research activities in 2007. Several of the 37 Research permits authorized work at multiple locations within the Monument; thus, the total number of permits in the figure below adds to more than 37. Map: K. Keller.

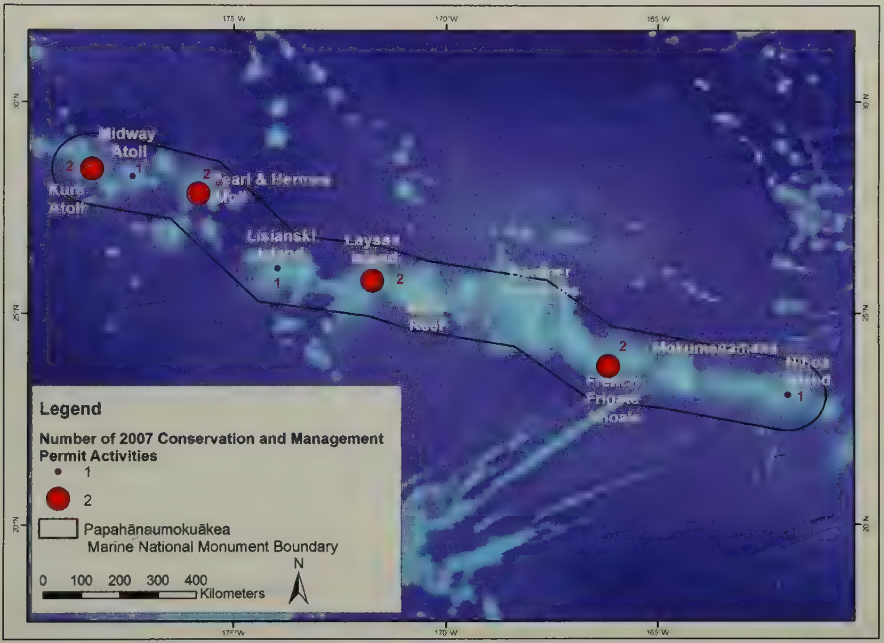


Figure 10.16. Locations of permitted Conservation and Management activities in 2007. Two of the five Conservation and Management permits authorized work at multiple locations within the Monument; thus, the total number of permits in the figure below adds to more than five. Map: K. Keller.

Education Activities by Location

NOAA Monument education activities in 2007 took place almost entirely aboard ship and during 12 shallow-water free dives, with land visits made only at Midway Atoll and Kure Atoll. Sites visited, where photos and video footage were taken, included Nihoa, Gardner Pinnacles, Laysan, Lisianski, Pearl and Hermes Atoll, Midway Atoll and Kure Atoll.

DLNR education activities took place aboard ship and during 13 shallow-water dives at French Frigate Shoals, Pearl and Hermes Atoll, and Midway Atoll (Figure 10.17). Photos and video footage were taken at each of these sites.

Native Hawaiian Practices Activities by Location

A single Native Hawaiian Practices permit was issued in 2007, to the University of Hawaii. Activities conducted under this permit included an overnight stay on Mokumanamana to conduct traditional ceremonies in observance of the summer solstice, and a stop off of the island of Nihoa to conduct additional ceremonies aboard ship (Figure 10.18).

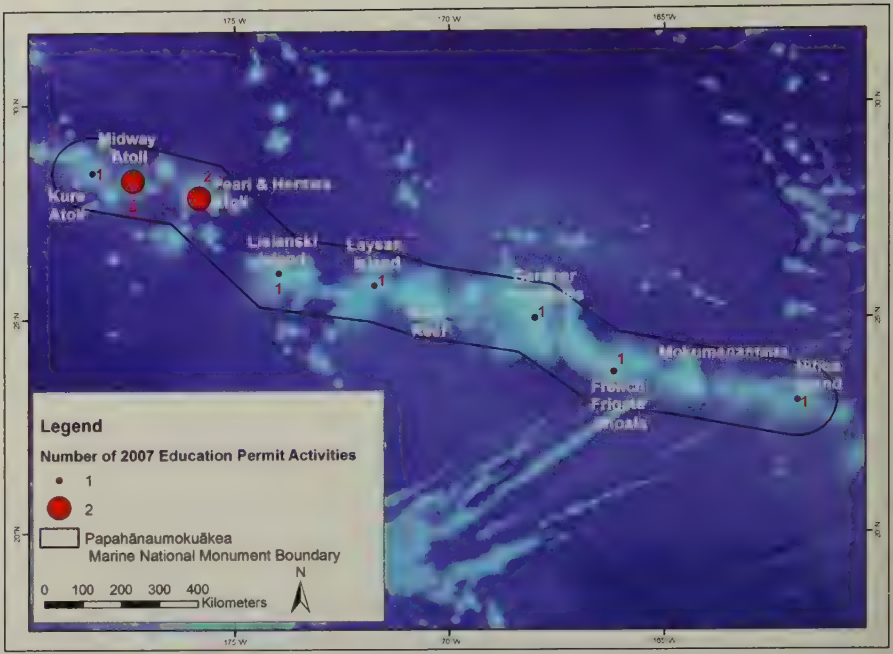


Figure 10.17. Locations of permitted Education activities in 2007. The two Education permits authorized work at multiple locations within the Monument; thus, the total number of permits in the figure below adds to more than two. Map: K. Keller.

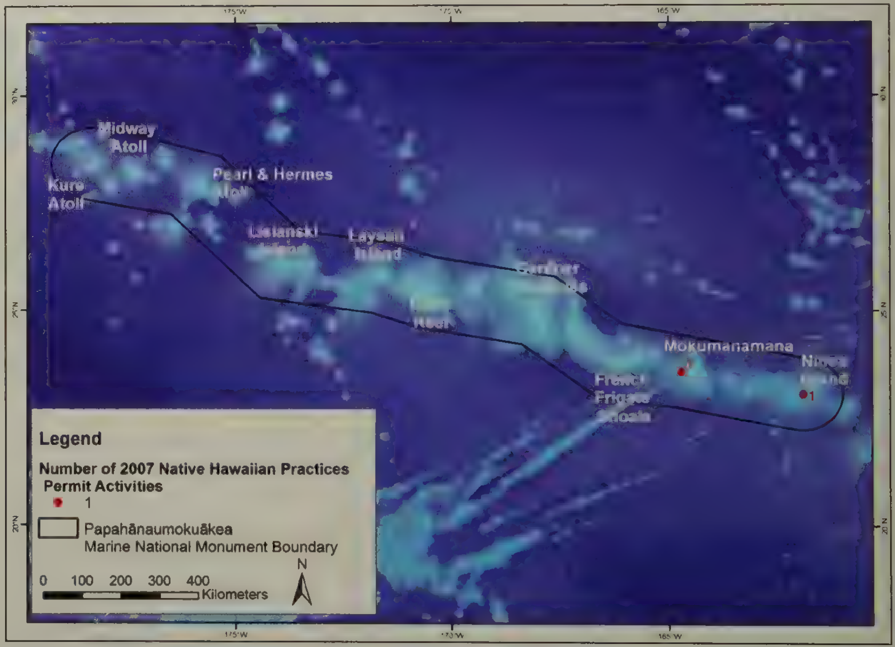


Figure 10.18. Locations of permitted native Hawaiian practices and activities in 2007. Map: K. Keller.

Special Ocean Use Activities by Location

Five Special Ocean Use permits were issued in 2007 occurring at Midway and French Frigate Shoals (Figure 10.19). Two of these permits were associated with the commemoration of the 65th Anniversary of the Battle of Midway and involved flight and ship transportation of World War II veterans and their families to Midway Atoll for the one-day celebration. A third Special Ocean Use permit was issued to the British Broadcasting Corporation for high-definition filming of tiger shark predation on albatross fledglings at French Frigate Shoals. The final two Special Ocean Use permits were issued for two individuals to conduct filming and still photography associated with NOAA Education and Research activities.

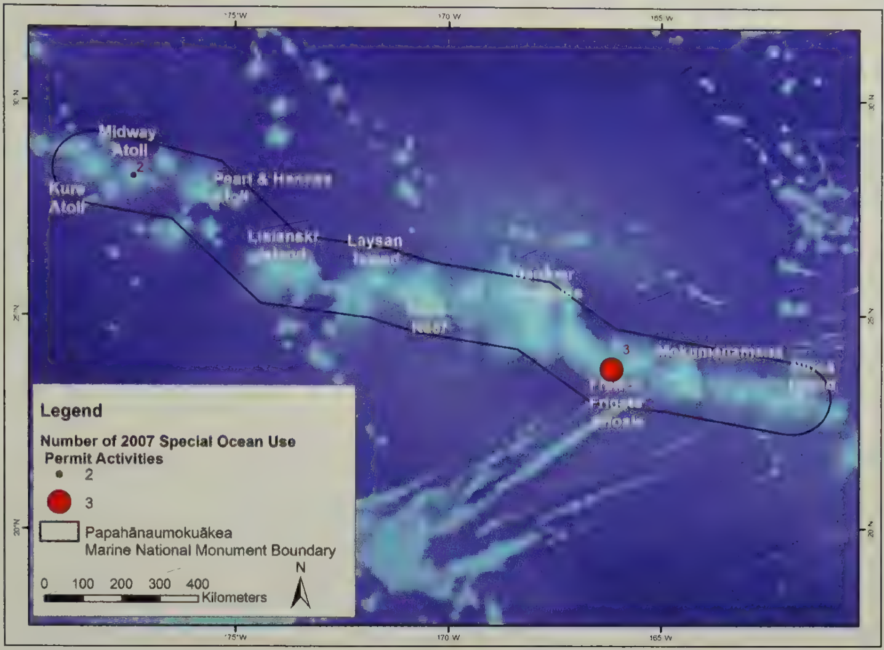


Figure 10.19. Locations of permitted Special Ocean Use activities in 2007. Map: K. Keller.

PMNM Relative Size and Visitation Rates

Table 10.9. Relative size and visitation rates for Hanauma Bay, Yosemite National Park, Great Barrier Reef Marine Park and Papahanaumokuakea Marine National Monument.

PROTECTED AREA PER DAY	SIZE	VISITATION RATE	PEOPLE PER ACRE
Hanauma Bay Nature Preserve	100 acres	3,000 people/day	30
Yosemite National Park	760,000 acres	9,600 people/day	0.01
Great Barrier Reef Marine Park	85,100,000 acres	5,423 people/day	0.00006
Papahanaumokuakea Marine National Monument	89,500,000 acres	115 people/day*	0.000001

*Includes 70 people per day at Midway Atoll.

Papahanaumokuakea Marine National Monument is the largest protected area in the United States, and is larger than all of the U.S. National Parks combined. It is also larger than almost all other protected marine areas in the world, including Great Barrier Reef Marine Park. Because of the protections put in place by Presidential Proclamation 8031, followed by the permitting system established by the Monument Management Board in 2007, the visitation rate to the Monument was significantly lower in 2007 compared to visitation rates to Hanauma Bay Nature Preserve, Yosemite National Park, and even Great Barrier Reef Marine Park (Table 10.9). The following figure (Figure 10.20) also illustrates the scale of Papahanaumokuakea Marine National Monument relative to western states on the mainland U.S. The Monument is larger than 46 of the 50 states, and if overlain on the west coast would span an area from Arizona through Nevada, Oregon, and Washington state.

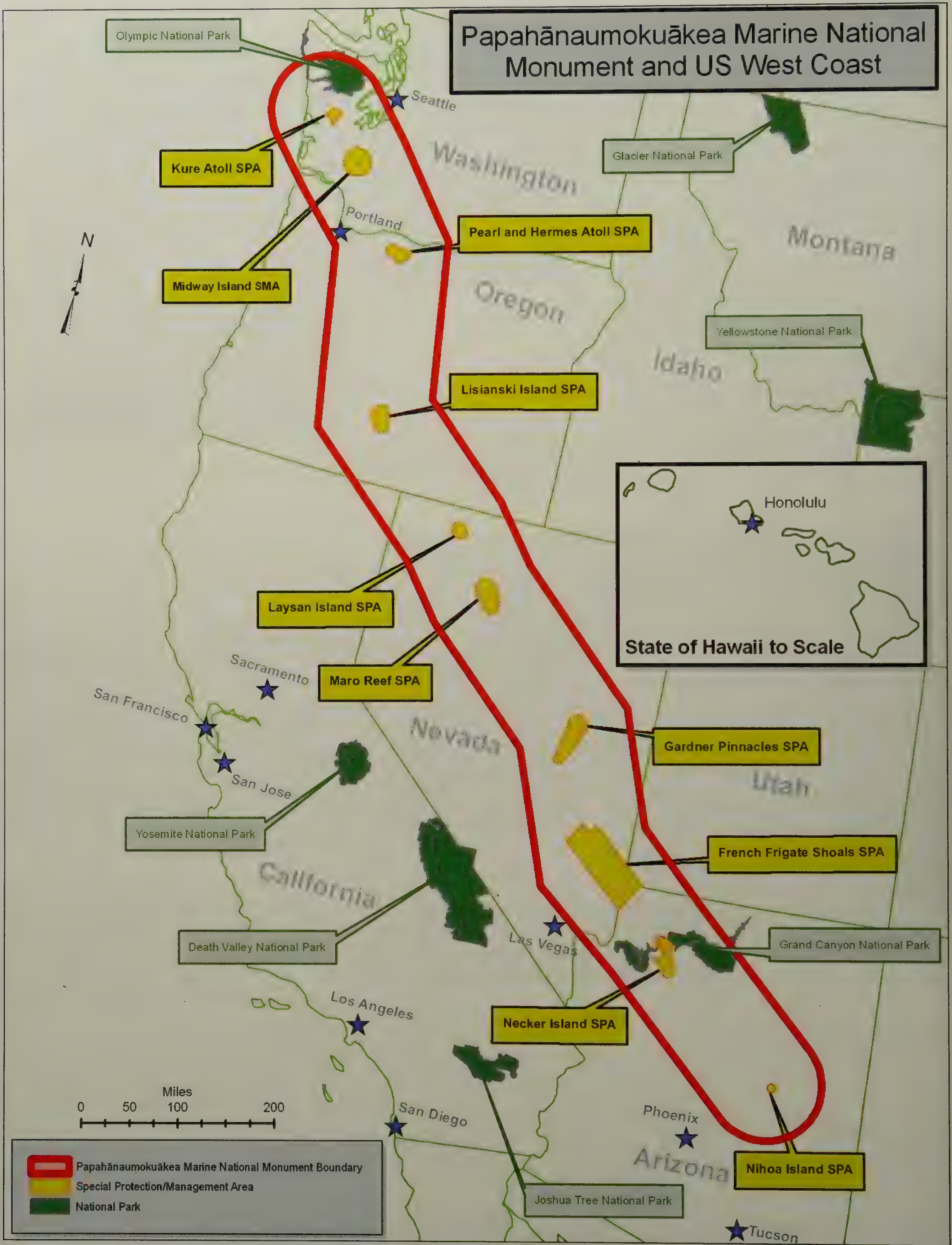


Figure 10.20. Size of the Monument relative to states on the west coast of the mainland U.S. Source: D. Turner, PMNM.

FUTURE DIRECTIONS AND IMPLICATIONS FOR A BIOGEOGRAPHIC ASSESSMENT TO SUPPORT HAWAIIAN ARCHIPELAGO SPATIAL MANAGEMENT

A primary use of implementing a marine biogeographic assessment for the NWHI was to further the understanding of the temporal and spatial coupling between the oceanographic characteristics, pelagic and benthic habitats, living marine resources and human uses that collectively comprise the NWHI ecosystem. The biogeographic assessment process is defined in this document's introduction and illustrated in Figure 10.21. Much of the data and information synthesized for this investigation addressed an area (e.g., oceanographic characteristics) much greater than the boundaries of the Monument or the individual atolls that comprise the island chain. However, the study area did not encompass the entire Hawaiian Archipelago that would place in context the biogeographic results for the NWHI when compared to the Main Hawaiian Islands (MHI). The exception is the work that has been done to characterize the shallow-water reef fish assemblages around both the heavily fished MHI and the very limited exploited reef fishes of the NWHI.

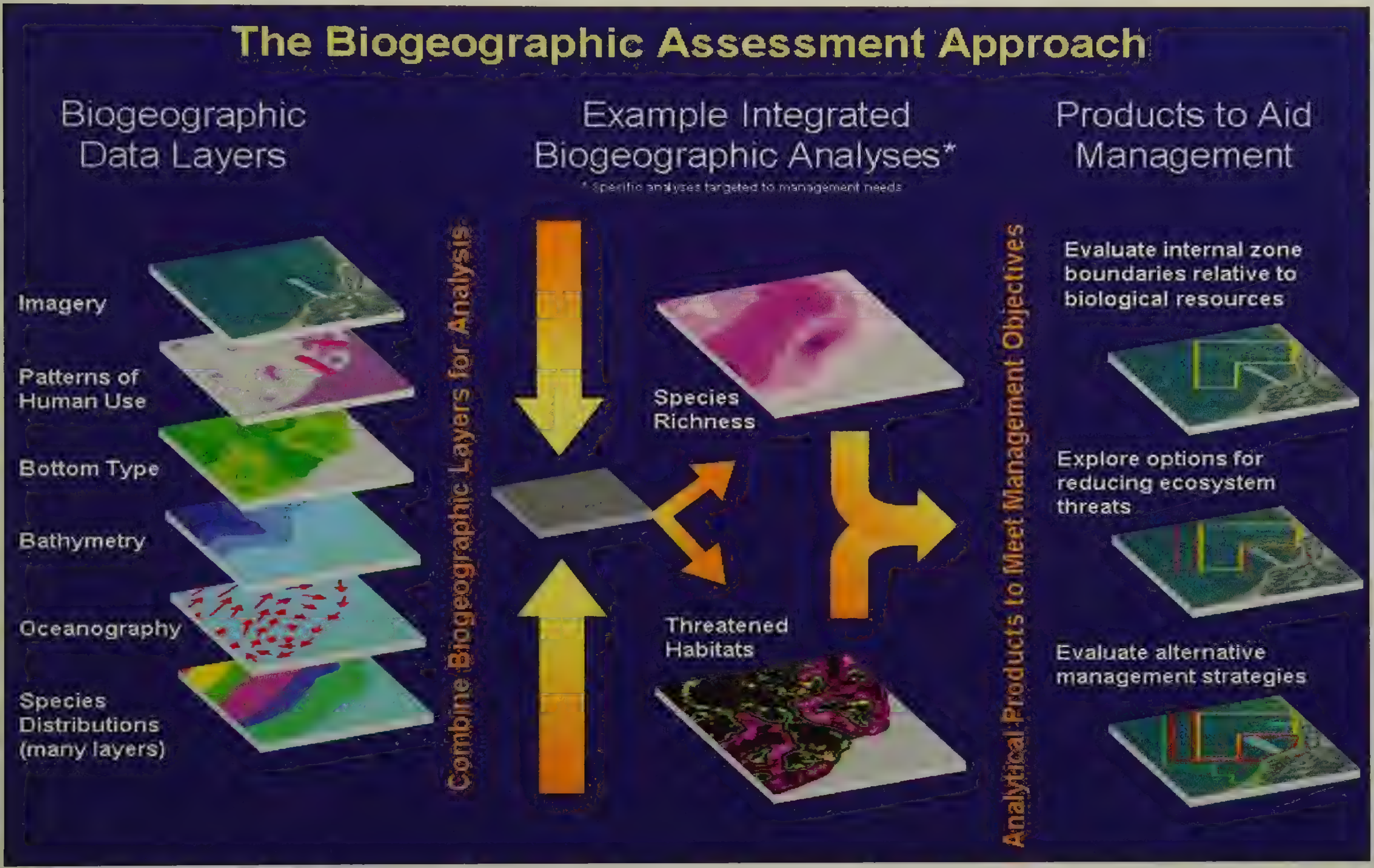
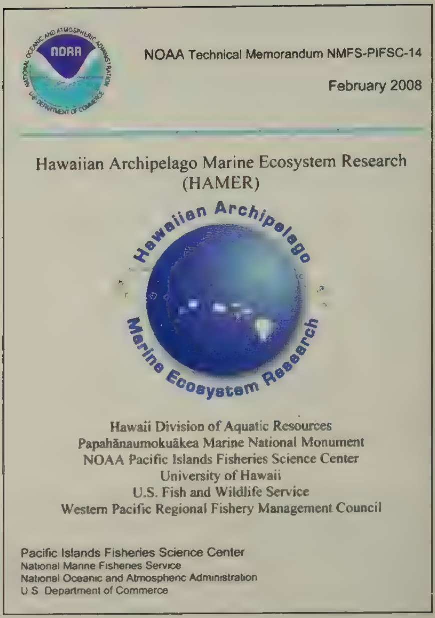

The Biogeographic Assessment Approach
Biogeographic Data Layers
Example Integrated Biogeographic Analyses*
* specific analyses targeted to management needs
Products to Aid Management
Imagery
Patterns of Human Use
Bottom Type
Bathymetry
Oceanography
Species Distributions (many layers)
Combine Biogeographic Layers for Analysis
Species Richness
Threatened Habitats
Analytical Products to Meet Management Objectives
Evaluate internal zone boundaries relative to biological resources
Explore options for reducing ecosystem threats
Evaluate alternative management strategies

Figure 10.21. Generalized biogeographic assessment process developed by CCMA-BB. Source: Kendall and Monaco, 2003.

The 2,500 km long Hawaiian Archipelago is unified by its geologic origin and geographic isolation. This vast area is subject to great spatial gradients in oceanography, erosion and geomorphology. The Hawaiian marine ecosystem has some of the highest marine endemism on the planet, with many species unique to the archipelago. Given these broad-scale characteristics, the recently published NOAA Technical Memorandum (NOAA, 2008), "Hawaiian Archipelago Marine Ecosystem Research" plan (HAMER), noted that Hawaii could serve as "a large scale archipelagic laboratory for the investigation of biophysical processes, comparing the protected and nearly pristine NWHI to the heavily used MHI to improve resources management in Hawaii and in comparable marine ecosystems worldwide (NOAA, 2008; Figure 10.22). HAMER identified six research themes important to the management of the Hawaiian Archipelago. They are:

- Ecosystem Indicators and Metrics;
- Native Biodiversity and Invasive Species;
- Connectivity;
- Human Interactions;
- Resilience and Recovery; and
- Modeling and Forecasting.



NOAA Technical Memorandum NMFS-PIFSC-14

February 2008

Hawaiian Archipelago Marine Ecosystem Research
(HAMER)

Hawaii Division of Aquatic Resources
Papahānaumokuākea Marine National Monument
NOAA Pacific Islands Fisheries Science Center
University of Hawaii
U.S. Fish and Wildlife Service
Western Pacific Regional Fishery Management Council

Pacific Islands Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

Figure 10.22. The Hawaiian Archipelago Marine Ecosystem Research.

Consistent with HAMER, the draft Papahanaumokuakea Marine National Monument Natural Resources Science Plan (NRSP), specifically cited a need for archipelagic-wide homogeneity in research planning and execution and adopted nearly identical thematic focus areas:

- Ecological Processes and Connectivity;
- Biodiversity and Habitats;
- Human Impacts;
- Indicators of Change and Monitoring; and
- Models and Forecasting.

Although HAMER is a plan for implementation over a ten year period, and the NRSP spans a shorter, five year period. Both plans provide the spatial and institutional framework to conduct research and integrate data and information in support of management of the Hawaiian Archipelago as a single, interconnected entity. With the recent increase in ecosystem monitoring data (e.g., Hawaii Coral Reef Assessment and Monitoring Program [CRAMP], MHI and NWHI Reef Assessment and Monitoring Programs [MHI/NWHI RAMP]), benthic habitat mapping (NOAA, 2007), and the assessment of habitats and associated fishes in and outside of marine protected areas (Friedlander et al., 2005, 2007), our ability to conduct archipelagic-wide research syntheses and biogeographic assessments is greatly enhanced. The biogeographic assessment process and this NWHI product directly support these multi-agency visions of HAMER and the PMNM NSRP, and provide a key starting point and many spatial data products that could be incorporated in a recommended MHI or archipelago-wide biogeographic assessment.

REFERENCES

Aeby, G.S., J.C. Kenyon, J.E. Maragos, and D.C. Potts. 2003. First record of mass coral bleaching in the Northwestern Hawaiian Islands. Coral Reefs 22(3): 246.

Amerson, A.B. 1971. The natural history of French Frigate Shoals, Northwestern Hawaiian Islands. Atoll Research Bulletin No. 150.

Baker J.D., C.L. Littnan, and D.W. Johnston. 2006. Potential effects of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands. Endangered Species Research, 4:1-10.

Balazs, G.H. and M. Chaloupka. 2004. Thirty-year recovery trend in the once depleted Hawaiian green sea turtle stock. Biological Conservation 117: 491-498.

Battista, T.A., B.M. Costa, and S.M. Anderson. 2007. Shallow-Water Benthic Habitats of the Main Eight Hawaiian Islands (DVD). NOAA Technical Memorandum NOS NCCOS 61, Biogeography Branch. Silver Spring, MD. http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd_07/welcome.html

Bustard, H.R. and K.P. Tognetti. 1969. Green sea turtles: a discrete simulation of density-dependent population regulation. Science. Vol. 163: 939-941.

Dameron, O.J., M. Parke, M.A. Albins, and R. Brainard. 2007. Marine debris accumulation in the Northwestern Hawaiian Islands: An examination of rates and processes. Marine Pollution Bulletin 54(4): 423-433.

Eldredge, L.G. 2005. Assessment of the potential threat of the introduction of marine nonindigenous species in the Northwestern Hawaiian Islands. Final report prepared for Environmental Defense, Waimanalo, Hawaii. 8 pp. Contribution No. 2005-001 to the Hawaii Biological Survey.

Eldredge, L.G. and J.T. Carlton. 2002. Hawaii marine bioinvasions: a preliminary assessment. Pacific Science 56(2):211-212.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436:686-688.

Feely, R.A.,C.L. Sabine, K. Lee, F.J. Millero, M.F. Lamb, D. Greeley, J.L. Bullister, R.M. Key, T.-H. Peng, A. Kozyr, T. Ono, and C.S. Wong. 2002. In situ calcium carbonate dissolution in the Pacific Ocean, Biogeoghemical Cycles, 16 (4), 1144.

Franklin, E. An assessment of vessel traffic patterns in the Northwestern Hawaiian Islands between 1994 and 2004. Marine Pollution Bulletin 56: 136-162.

Friedlander, A.M., G. Aeby, R. Brainard, A. Clark, E. DeMartini, S. Godwin, J. Kenyon, R. Kosaki, J. Maragos, and P. Vroom. 2005. The State of Coral Reef Ecosystems of the Northwestern Hawaiian Islands. pp. 270-311. In: J. Waddell (ed.), The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2005. NOAA Technical Memorandum NOS NCCOS 11. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 522 pp.

Friedlander A.M., G. Aeby, S. Balwani, B. Bowen, R. Brainard, R. Clark, J. Kenyon, J. Maragos, C. Meyer, P. Vroom, and J. Zamzow. 2008. The state of coral reef ecosystems of the northwestern Hawaiian Islands. pp. 270-311 In: Waddell, J.E. and A.M. Clarke (eds), The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.

Godwin, S., K.S. Rodgers, and P.L. Jokiel. 2006. Reducing potential impact of invasive marine species in the Northwestern Hawaiian Islands Marine National Monument. Report to: Northwest Hawaiian Islands Marine National Monument Administration.

Godwin, L.S. 2008. The marine invertebrate species associated with the biofouling of derelict fishing gear in the Papahanoumokuakea–Marine National Monument. Report submitted to NOAA-NMFS, PIFSC, Coral Reef Ecosystem Division. (In Review).

Halpern, B.S., S. Walbridge, K.A. Selkoe, C.B. Kappel, F. Micheli, C. D'Agrosa, J.F. Bruno, K.S. Casey, C. Ebert, H.E. Fox, R. Fujita, D. Heinemann, H.S. Lenihan, E.M.P. Madin, M.T. Perry, E.R. Selig, M.Spalding, R.Steneck, and R. Watson. 2008. A Global Map of Human Impact on Marine Ecosystems. Science. Vol. 319: 948-952.

Halpern, B.S., K.A. Selkoe, F. Micheli, and C.V. Kappel. 2007. Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. Conservation Biology Vol. 21 No. 5, 1201-1315.

Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. Marine Freshwater Research 50:839-866.

Hoeke, R., R. Brainard, R. Moffitt, and M. Merrifield. 2006. The role of oceanographic conditions and reef morphology in the 2002 coral bleaching event in the Northwestern Hawaiian Islands. Atoll Res. Bull. 543: 489-503.

Hourigan, T.F., S.E. Lumsden, G. Dorr, A.W. Bruckner, S. Brooke, and R.P. Stone. 2008. State of Deep Coral Ecosystems of the United States: Introduction and National Overview. In: Waddell, J.E. and A.M. Clarke (eds.), 2008. The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.

IPCC. 2001. Climate Change 2001: Synthesis Report IPCC, Intergovernmental Panel on Climate Change.

IPCC. 2007. Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability (Contributions of Working Group II) IPCC, Intergovernmental Panel on Climate Change. http://www.ipcc.ch.

Johnston, D.W., M.E. Chapla, L.E. Williams, and D.K. Mattila. 2007. Identification of humpback whale *Megaptera novaeangliae* wintering habitat in the Northwestern Hawaiian Islands using spatial habitat modeling. Endangered Species Research. Vol.3:249-257.

Jokiel, P.L. and E.K. Brown. 2004. Global warming, regional trends, and inshore environmental conditions influence coral bleaching in Hawaii. Global Change Biology 10:1627-1641.

Kenyon, J.C. and R.E. Brainard. 2006. Second recorded episode of mass coral bleaching in the Northwestern Hawaiian Islands. Atoll Research Bulletin 543: 505-523.

Kenyon, J.C. and R.E. Brainard. 2006. Second recorded episode of mass coral bleaching in the Northwestern Hawaiian Islands. Atoll research bulletin. 543:505.

Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, and L.L. Robbins. 2006. Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18-20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA and the U.S. Geological Survey. 88 pp.

Kleypas, J.A. and C. Langdon. 2006. Coral Reefs and Changing Seawater Carbonate Chemistry. Coastal and Estuarine Studies 61:73-110.

Kleypas, J.A., R.W. Buddemeier, D. Archer, J.-P. Gattuso, C. Langdon, and B.N. Opdyke. 1999. Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs. Science 284:118-120.

Naughton, M.B., M.D. Romano, and T.S. Zimmerman. 2007. A conservation action plan for Black-footed Albatross (*Phoebastria nigripes*) and Lasan Albatross (*P. immutabilis*), Ver. 1.0.

National Marine Fisheries Service. 2007. Recovery Plan for the Hawaiian Monk Seal (*Monachus schauinslandi*). Second revision. National Marine Fisheries Service, Silver Spring, MD. 165 pp.

NOAA (National Oceanic and Atmospheric Administration) Fisheries. 1991. Humpback Whale Recovery Plan, Silver Spring, MD.

NOAA (National Oceanic and Atmospheric Administration). 2003. Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands (Draft). Center for Coastal Monitoring and Assessment, Silver Spring, MD. 160 pp.

NOAA Coral Reef Watch. 2008. http://coralreefwatch.noaa.gov/satellite/current/sst_series_24reefs.html

NOAA (National Oceanic and Atmospheric Administration) Fisheries. 2006a. Fin Whale Recovery Plan, Silver Spring, MD.

NOAA (National Oceanic and Atmospheric Administration) Fisheries. 2006b. Sperm Whale Recovery Plan, Silver Spring, MD.

NOAA (National Oceanic and Atmospheric Administration) Fisheries. 1998. Blue Whale Recovery Plan, Silver Spring, MD.

NOAA Fisheries and FWS (U.S. Fish and Wildlife Service). 1998a. Recovery Plan for U.S. Pacific Populations of the Hawksbill Turtle (*Eretmochelys imbricata*). National Marine Fisheries Service, Silver Spring, MD

NOAA Fisheries and FWS (U.S. Fish and Wildlife Service). 1998b. Recovery Plan for the U.S. Pacific Populations of the East Pacific Green Turtle (*Chelonia mydas*). National Marine Fisheries Service, Silver Spring, MD.

NOAA Fisheries and FWS (U.S. Fish and Wildlife Service). 1998c. Recovery Plan for U.S. Pacific Populations of the Loggerhead Turtle (*Caretta caretta*). National Marine Fisheries Service, Silver Spring, MD.

NOAA Fisheries and FWS (U.S. Fish and Wildlife Service). 1998d. Recovery Plan for U.S. Pacific Populations of the Leatherback Turtle (*Dermochelys coriacea*). National Marine Fisheries Service, Silver Spring, MD.

NOAA Fisheries and FWS (U.S. Fish and Wildlife Service). 1998e. Recovery Plan for U.S. Pacific Populations of the Olive Ridley Turtle (*Lepidochelys olivacea*). National Marine Fisheries Service, Silver Spring, MD.

NOAA Fisheries and FWS (U.S. Fish and Wildlife Service). 2007. ESA Reviews for Federally Listed Sea Turtles. http://www.fws.gov/northflorida/SeaTurtles/2007-Reviews/2007-sea-turtle-ESA-reviews.htm.

NOAA Pacific Islands Fisheries Science Center. 2008. Hawaiian Archipelago Marine Ecosystem Research. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFSPIFSC-14, 103 pp.

NOAA Satellite and Information Service. 2007. Sea surface temperature datasets.

NOAA, USFWS, State of Hawaii. 2008. http://papahanaumokuakea.gov/resource/permits.html.

Nott, J.F. 2003. Intensity of prehistoric tropical cyclones. Journal of Geophysical Research-Atmospheres 108.

Nott, J. 2004. Palaeotempestology: the study of and implications Review article prehistoric tropical cyclones - a review for hazard assessment. Environment International 30:433-447.

Nott, J., J. Haig, H. Neil, and D. Gillieson. 2007. Greater frequency variability of landfalling tropical cyclones at centennial compared to seasonal and decadal scales. Earth and Planetary Science Letters 255:367-372.

Papahanaumokuakea Marine National Monument. 2008. Papahanaumokuakea Marine National Monument Draft Management Plan.

Parrish, F.A. and A.R. Baco. 2008. State of Deep Coral Ecosystems in the U.S. Pacific Islands Region: Hawaii and the U.S. Pacific Territories. In: Waddell, J.E. and A.M. Clarke (eds.), 2008. The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.

Selkoe, K.A., B.S. Halpern, and R.J. Toonen. 2008. Evaluating anthropogenic threats to the Northwestern Hawaiian Islands. Aquatic Conservation: Marine and Freshwater Ecosystems. Vol 18:7. Pp 1149-1165.

The Royal Society. 2005. Ocean Acidification due to increasing atmospheric carbon dioxide. 59 pp.

U.S. Fish and Wildlife Service 2005. Short-tailed Albatross Draft Recovery Plan. Anchorage, AK. 62 pp. http://ecos.fws.gov/tess_public/SpeciesRecovery.do?sort=1.

U.S. Fish and Wildlife Service. 2008. Short-tailed Albatross Recovery Plan. Anchorage, AK, 105 pp.

USFWS. 2008. http://www.fws.gov/midway/.

Webster, P.J., G.J. Holland, J.A. Curry, and H.-R. Chang. 2005. Changes in Tropical Cyclone Number, Duration and Intensity in a Warming Environment. Science 309:1844-1846.

PERSONAL COMMUNICATIONS

Balazs, G.H. National Marine Fisheries Service, Honolulu, Hawaii, U.S.A.

Maragos, J.E. U.S. Fish and Wildlife Service, Honolulu, HI, U.S.A.

National Oceanic and Atmospheric Administration

Mary M. Glackin , *Deputy Under Secretary for Oceans and Atmosphere*

National Ocean Service

John H. Dunnigan, *Assistant Administrator for Ocean Service and Coastal Zone Management*

DEPARTMENT OF COMMERCE · UNITED STATES OF AMERICA